What does climate change mean for the ecology, invasiveness and management of tephritid pests in Australia?

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DECLARATION

I, Sabira Sultana, hereby declare that the work of my thesis entitled "*What does climate change mean for the ecology, invasiveness and management of Tephritidae pests in Australia?*" submitted to the Department of Biological Sciences, Macquarie University, Sydney, for the award of a Doctor of Philosophy Degree is my original research work. This work has not been submitted in any other form for a higher degree at any other university or institution. To the best of my knowledge and belief, the thesis contains no material previously written by another person except where due reference is made.

All work by other researchers is properly acknowledged.

SIGN [redacted]

SABIRA SULTANA

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ABSTRACT

Tephritid fruit flies are among the most devastating pests to Australia's multi-billion-dollar horticulture industry. The Australian National Fruit Fly Strategy (2010) identified 46 native and exotic species as 'high priority pests' of concern, the management of which are vital for plant protection and biosecurity. While considerable research attention has been given to several of these species, to date the potential for climate change to alter the distribution and relative risks of these species has been largely overlooked. My thesis aims to bridge this gap. In addition to the introduction and conclusion, my thesis consists of three data chapters and a review chapter. The thesis is structured as a series of papers, one of which has been published and with another accepted. Chapters two and three utilised the species distribution model Maxent to map suitable habitat for Tephritidae pests under current and future climate scenarios for 2030, 2050 and 2070. Maxent is a correlative SDM that has been widely used to assess the distribution of suitable habitat for a broad range of pest and invasive species. Chapter two focused on the most economically costly of the Tephritidae pests in Australia – the Queensland fruit fly, *Bactrocera tryoni* (Froggatt) (Qfly), which attacks more than 100 native and introduced host plant species. My model indicates that south-western Western Australia, northern regions of the Northern Territory, eastern Queensland, and much of south-eastern Australia, southern Victoria and eastern Tasmania are currently suitable for Qfly. It also indicates that most areas that are currently suitable will remain so throughout much of this century. My results provide guidance on the potential exposure of Australia's horticultural industry to Qfly as climate changes. In Chapter three, I extended my modelling approach to the 11 native, high priority, economically important tephritid pests that are present within Australia. In this chapter I identified 'hotspots' (regions suitable to multiple pest species), to guide Australia's horticulture industries in developing effective monitoring and management strategies. My results highlight that the Wet Tropics is likely to be vulnerable to all 11 species until at least 2070. As the century progresses, the east coast of Australia, Cape York Peninsula and Northern Territory are likely to remain vulnerable to multiple species, however, extrapolation to novel climates in these areas decreases confidence in model projections. My results also indicate that the vulnerability of major horticulture areas in eastern Queensland, southern-central regions of New South Wales and southern Victoria to these pests may increase. Chapter four represents a risk assessment of 19 non-native invasive species that are currently not present in Australia but that have been identified as having the potential to pose considerable risks if they establish. I assessed their relative establishment likelihood under current and future climates by combining maps of a) regions of Australia with a climate similar to species' known ranges, b) a key arrival pathway (i.e. the movement of people entering Australia from host countries) and c) the distribution of horticultural lands. I found that *Bactrocera dorsalis* has the highest establishment likelihood under all climate scenarios, followed by *Zeugodacus cucurbitae* and *B. latifrons*. Chapter five presents a literature review of the potential impacts of climate change on tephritid fruit flies, particularly those in Australia. In doing so, I outline likely responses, key knowledge gaps, and implications for horticultural industries. My thesis provides the horticultural industry in Australia with a greater understanding of the relationship between fruit fly pests and climate change, and highlights the importance of long-term vigilance to ensure the long-term security of this industry.

CHAPTER DECLARATION

This thesis is structured and written to conform to the “thesis by publication” format. It is organized into six chapters: an introductory chapter, three data chapters, one review chapter and a general discussion chapter. My contribution to each chapter is as follows:

Chapter One: Introduction

I wrote this chapter with feedback and editing from Assoc Prof Linda Beaumont.

Chapter Two: Potential impacts of climate change on habitat suitability for the Queensland fruit fly

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Sultana, Baumgartner and Beaumont designed the research. Species data were collated by Sultana, Baumgartner, Dominiak, Royer and Beaumont. The species distribution modelling was undertaken by Sultana and evaluated by Baumgartner, Dominiak, Royer and Beaumont. Manuscript was drafted by Sultana with feedback from Baumgartner, Dominiak, Royer and Beaumont. Slight modifications were made to the thesis chapter, compared to the publication, to conform to thesis requirements.

Chapter Three: Impacts of climate change on high priority fruit fly species in Australia

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Sultana, Baumgartner and Beaumont designed the research. Data were collated by Sultana with feedback from Baumgartner, Dominiak, Royer and Beaumont. Modelling was undertaken by Sultana and evaluated by Baumgartner, Dominiak, Royer and Beaumont. Sultana drafted the Manuscript with feedback from Baumgartner, Dominiak, Royer and Beaumont. Slight modifications were made to the thesis chapter, compared to the publication, to conform to thesis requirements.

Chapter Four: Estimating the current and future risk of exotic fruit fly species establishing in Australia (in prep for submission to Scientific Reports).

Sultana, Baumgartner and Beaumont designed the experiment, with advice from Dr James Camac (University of Melbourne). Data on tephritids and host plants were collated by Sultana with feedback from Baumgartner and Beaumont. Climate matching was undertaken by Sultana with the assistance of Baumgartner and Beaumont. The map of dispersal of air passengers across the country was developed by Baumgartner with input from Camac. Sultana prepared the Manuscript with feedback from Baumgartner and Beaumont.

Chapter Five: The impact of climate change on tephritid pests (in prep for submission to Scientific Reports).

I drafted the majority of this chapter, with input from Dr Md-Mohasinul Haque, Baumgartner and Beaumont.

Chapter Six: Thesis Discussion and Conclusion

I organized and wrote this chapter with feedback and editing from Baumgartner and Beaumont.

DEDICATION

To my loving son Maahir Hossain, my dearest mum, my beloved husband Shahidul Moazzem Hossain Rocky, and my sweetest sister Himel Sultana.

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Table of Contents

CHAPTER ONE

Thesis Introduction

Introduction

Globally, climate is changing, primarily due to human-induced increases in the concentration of greenhouse gases (GHG). Since the start of the Industrial Revolution (~1750), the concentration of carbon dioxide (CO_2) has risen from 280 ppm to 410 ppm (as at October 2019, www.climate.nasa.gov), with the CO_2 equivalent of other GHGs reaching 500 ppm in 2017 (BoM and CSIRO 2018). As a consequence, global average temperature has increased by approximately 1.1°C (WMO 2019), with the period 2015-2019 likely to have been the warmest of any equivalent period on record globally (WMO 2019).

The velocity of future anthropogenic climate change will be influenced by the magnitude of GHG emissions, which will be driven by technological changes, economic, lifestyle and policy decisions (Moss et al. 2010). As such, projections of likely increases to global mean surface temperature for 2081–2100, relative to 1986–2005, span 0.3–1.7°C to 2.6–4.8°C, under Representative Concentration Pathways (RCP) 2.6 and 8.5, respectively (IPCC 2014a). As temperatures increase, so too will the frequency and duration of extreme heat events (IPCC 2014a). Rainfall patterns will also shift, although with less spatial uniformity than projected temperature increases (BoM and CSIRO 2018). Under RCP 8.5, high latitudes and equatorial regions are likely to experience increased precipitation, whereas many mid-latitude and subtropical dry regions may experience the opposite trend (IPCC 2014b). Extreme rainfall events will also likely become more intense and frequent in most regions (BoM and CSIRO 2018).

Australia is one of the most climatically variable countries in the world (Manolas 2010, Stokes and Howden 2010). Australia's temperature has increased by more than 1°C since 1910, with increases in extreme heat events and the severity of drought conditions (BoM and CSIRO 2018). The rise in temperature has been observed across Australia in all seasons, and to a greater extent at night compared to daytime (BoM and CSIRO 2018).

Australia's rainfall is highly variable, however recent decades have experienced a drying trend in the south of the continent (Alexander et al. 2007, Gallant et al. 2007). Since 1970, May–July rainfall in the southwest has decreased by 20%, while since the 1990s, the southeast has experienced declines of ~11% over April-October. In contrast, the opposite trend has occurred in northern Australia with rainfall increasing since the 1990s (Jones et al. 2009, BoM and CSIRO 2018). There has also been an increase in the number of high fire weather danger days and a longer fire season for southern and eastern Australia (BoM and CSIRO 2018).

By 2030, mean annual temperature in Australia is projected to increase by 0.6–1.3 °C compared to the period 1986–2005, under RCP 8.5 (CSIRO and Bureau of Meteorology 2015). By 2090, this increase is projected to range from 0.6–1.7 °C (RCP 2.6) to 2.8–5.1 °C (RCP 8.5) (CSIRO and Bureau of Meteorology 2015), with average warming likely to be higher in inland Australia compared with coastal areas. The average number of days above 35 °C is projected to more than double for all major metropolitan regions by 2090, with the number of frost days declining to less than half (CSIRO and Bureau of Meteorology 2015). Projections of rainfall changes are hampered by substantial variation across global climate models. There is little agreement in the direction of change of annual precipitation across northern Australia, although there is moderate agreement that winter and spring precipitation will decline. There is also moderate agreement for a substantial decline in annual precipitation across eastern Australia, with this predominantly occurring in winter and spring. There is, however, high agreement that substantial declines in winter and spring precipitation will occur across the southern regions of the continent (CSIRO and Bureau of Meteorology 2015).

Biological Responses to Climate Change—a Brief Overview

There is already clear evidence of biological and ecological responses to anthropogenic climate change (Parmesan 2006, Scheffers et al. 2016). A meta-analysis of 94 ecological processes, from multiple levels of biological organisation, found that 82% of processes demonstrated evidence of responses to climate change (Scheffers et al. 2016). These included micro-evolution, phenological adjustments, range shifts, and changes to meta-populations and community composition.

To date, the processes for which we have the greatest amount of data are range shifts and phenological (typically related to spring) adjustments. For example, Chen et al.'s (2011) meta-analysis of range shifts among 764 species across multiple continents found that shifts to higher elevations have occurred at a median rate of 11.0 meters per decade, while poleward shifts have occurred at a median rate of 16.9 km per decade. These values are faster than previous estimates by two and three times, respectively. A comparison of the range shifts of British breeding birds over the periods 1988–1991 and 2008–2011 documented an average shift northward of 13.5 km (Gillings et al 2015). Similar responses have been reported amongst insects. An early study of the fingerprint of climate change found that of 35 non-migratory European butterfly species, 63% had extended their range northward by 35–240 km, over the last century, whereas only 3% extended to the south (Parmesan et al. 1999). A meta-analysis by Bebber et al. (2013) of crop pests and pathogens found an average poleward range shift of 2.7 ± 0.8 km per year, since 1960.

Across Europe, an analysis of observations of 561 plant and animal species from 1971–2000 found that spring events had advanced 2.5 days per decade (Menzel et al. 2006). A similar meta-analysis of phenological events from southern hemisphere species found that those associated with spring had advanced 4.2 days per decade since ~1960 (Chambers et al. 2013).

Tephritidae Fruit Flies as Pests

Fruit fly species belonging to the family Tephritidae are among the most devastating pests to horticulture industries worldwide due to their large host breadth, short generation times, large population sizes and wide climatic tolerances (Fletcher 1987, White and Elson-Harris 1992, Plant Health Australia 2018). These species pose serious threats to fruit and vegetable crops and cause a range of impacts including direct yield loss, loss of market access and increased quarantine costs (White and Elson-Harris 1992, Vargas et al. 2015, Plant Health Australia 2018).

Within the Tephritidae, five genera (*Anastrepha, Bactrocera, Ceratitis, Rhagoletis and Zeugodacus*) pose the greatest threat to horticulture. Many of these species are highly polyphagous (White and Elson-Harris 1992, Godefroid et al. 2015) and are distributed throughout temperate, tropical and subtropical regions. For instance, *Bactrocera dorsalis* Hendel (Oriental fruit fly) infests more than 150 fruit and vegetable crops (Hui 2001). This species is native to Asia but has spread to more than 65 countries and is recognised as one of the most destructive fruit flies (CABI 2019). Within the genus *Ceratitis*, *C. capitata* Wiedemann (Mediterranean fruit fly [Medfly]) is also highly polyphagous, infesting over 300 cultivated and wild fruits (Lysandrou 2009). Its rapid generation time and ability to withstand cooler climates than most other fruit flies have resulted in it spreading throughout Africa, the Mediterranean, South America and Australia.

Environmental factors such as temperature and rainfall, and the availability of host plants are the main factors determining the distribution and survival of fruit flies (Bateman 1972, Meats 1981, Yonow and Sutherst 1998, Rwomushana et al. 2008, Vayssières et al. 2009, Grout and Stoltz 2014, Bota et al. 2018). The rate of reproduction of *B. dorsalis* is higher in tropical (5–10 generations per year) compared to subtropical regions (< 4 generations per year) (Hui 2001, Liu and Ye 2006). Vargas et al. (1997) reported that *Zeugodacus cucurbitae* Coquillett, *B. dorsalis, B. latifrons* Hendel and *C. capitata* are well adapted to temperatures between 18–29 °C, with the optimum temperature for reproduction being 24 °C. Similarly, the optimum temperature range for the development and reproduction of *B. dorsalis* spans 15–34 °C (Chen and Ye 2007, Ekesi et al. 2006, Rwomushana et al. 2008). Populations of the melon fruit fly (*Z. cucurbitae* Coquillett, previously known as *B. cucubitae*) decline when temperature exceeds 32 °C (Dhillon et al. 2005) or rainfall is inadequate (Nishida 1963, Wazir et al. 2019). The survival of immature stages of *Anastrepha ludens* Loew (Mexican fruit fly) decreases considerably during periods of low rainfall, leading to population declines during the dry season (Vayssières et al. 2009). Rainfall has also been reported to influence the emergence rate of *A. ludens* (Baker 1944) and *Rhagoletis pomonella* Walsh (Oatman 1964).

Host plants are used by fruit flies for sheltering, feeding, mating and larval development (Rwomushana et al. 2008, Vayssières et al. 2009). During oviposition, Tephritid females deposit their eggs into the flesh of the ripening fruit of their plant host (White and Elson-Harris 1992, Sumrandee et al. 2011). In doing so, the flies can cause both direct and indirect damage to the fruits. Direct damage occurs because the eggs hatch and the larvae feed on the fruits (Bateman 1972, Clarke et al. 2011) thereby causing damage to the plants' tissue (Hancock et al. 2000, Clarke et al. 2005). Indirect damage can occur because pathogenic microorganisms can penetrate the fruit via the hole left by the female's ovipositor (Uchôa 2012).

High Priority fruit flies in Australia and their Economic Costs

Numerous fruit fly species have been recorded in Australia, and the National Fruit Fly Strategy has identified 46 species as 'high priority pests' that threaten the biosecurity of Australia's horticulture (Plant Health Australia 2008). These flies belong to five genera: *Anastrepha, Bactrocera, Ceratitis, Rhagoletis,* and *Zeugodacus*. Nine of them are native to Australia. Of the 37 exotic high priority pests, only two are currently found in Australia (*C. capitata* [Medfly] and *B. frauenfeldi* Schin.) (Plant Health Australia 2008). *Bactrocera dorsalis* was detected in 1995 in northern Queensland, but it was quickly eradicated (Fay et al. 1997). However, the remaining species have been reported to cause economic costs to horticulture elsewhere (Plant Health Australia 2008).

One of the most polyphagous fruit flies is Medfly, which causes serious damage to fresh fruits globally (Qin et al. 2015). Native to sub-Saharan Africa, this species is one of the most damaging fruit pests globally. Medfly was first detected in California in 1975 (APHIS 1992), and outbreaks in that state have cost nearly US$500 million over a 25-year period (Szyniszewska and Tatem 2014). In Brazil, Medfly has been estimated to cause economic losses of US $242 million per year (Qin et al. 2015).

The melon fruit fly (*Z. cucurbitae*) is native to Asia but has invaded a wide number of countries in temperate, tropical and subtropical regions. Horticultural losses caused by this species range from 30–100% (Dhillon et al. 2005, Wazir et al. 2019). For instance, in India 50% of cucurbits are partially or completely damaged by this pest each year (Wazir et al. 2019). A major pest of olives is the Olive fruit fly (*B. oleae* Rossi), which has been estimated to cause losses of $800 million per year in the Mediterranean basin, requiring more than $100 million annually to combat it (Bueno and Jones 2002). The solanum fruit fly (*B. latifrons*), native to south and south-east Asia, has been found to damage 60–80% of red pepper crops in Malaysia (Vijaysegaran 1997). The apple maggot fly (*R. pomonella*) is currently only distributed in North America (CABI 2019), where it has a substantial impact on the apple industry in the western United States (Zhao et al. 2007), causing 78–100% crop losses (Chen and Shen 2002)

However, of the 46 high priority pests, it is the Queensland Fruit Fly (*B. tryoni* Froggatt) that currently causes the greatest economic cost to Australian horticulture.

The Queensland Fruit Fly (Bactrocera tryoni)

The Queensland fruit fly (Qfly) is endemic to the rainforests of Australia's east coast. As rainforests were cleared and cultivation of exotic fruits increased, this species expanded its geographic and host range (Bateman 1968). Qfly is now distributed throughout eastern Queensland, as well as parts of NSW, and extends into coastal Victoria and the Northern Territory (Meats 1981, Osborne et al. 1997, Dominiak and Daniels 2012). Tasmania and South Australia are currently considered free of Qfly (FAO 2006).

Qfly is highly polyphagous, attacking more than 110 host species, many of which are commercial crops such as citrus, nuts, stone and pome fruit, tomato, banana and coffee (Hancock et al. 2000). Qfly likely has a broader host range than is currently recognised (Clarke et al. 2011), and this requires further investigation along with a comparative analysis of the relative susceptibility of its hosts and associated fruit traits.

Temperature and rainfall play an important role in determining the distribution and survival of Qfly (Bateman 1972, Meats 1981, Yonow and Sutherst 1998). Qfly adults can breed throughout the year in warm conditions, although breeding will cease in winter in temperate regions of Australia (O'Loughlin et al. 1984, Muthuthantri et al. 2010). The optimum temperature range for egg maturation, however, is 13–26 °C (Pritchard 1970, Fletcher 1975). There is also a strong positive correlation between rainfall and the peak numbers of Qfly (Bateman 1972), with fecundity reduced in drought conditions (Bateman 1972). Rainfall can also indirectly impact Qfly via its impacts on host tree growth, distribution and fruiting. For example, shrivelled fruit on trees may drop prematurely, resulting in significant egg loss (Bateman 1968).

Objectives and Structure of the Thesis

Climate change will impact insect development, abundance, and distributions, thereby altering patterns of invasion (Hill et al. 2016). Increasing temperatures and changing precipitation patterns will likely improve the suitability of a region for some species while decreasing it for others (Yonow and Sutherst 1998, Stephens et al. 2007, Stephens et al. 2016). Many tephritid pests have tropical and subtropical origins (Stephens et al. 2016), and as temperatures increase, species' ranges are likely to move to higher latitudes and altitudes (Stephens et al. 2007, Ni et al. 2012, Fu et al. 2014). Warming in temperate regions may improve conditions for establishment through fewer frost days, a longer growing season and greater frequency of warm nights (Papadopoulos et al. 2013).

Given the impact and economic cost of fruit flies to Australian horticulture, it is vital for stakeholders to be informed about how climate change may alter the risks posed by fruit flies. To this end, the overarching goals of my thesis were to assess:

1) how climate change may impact the distribution of suitable habitat for Qfly – the most damaging of the fruit flies within Australia.
2) the distribution of hotspots – regions suitable for 11 of the most damaging fruit fly pests currently within Australia – under current and future climates.
3) the relative risk, under current and future climate, of 19 exotic tephritid species absent from Australia, but classified as "high priority pests".

The thesis is structured as a series of papers, one of which has been published (Sultana et al. 2017) and another accepted (Sultana et al. PLoS One). In addition to the introduction (Chapter One) and discussion (Chapter Six), my thesis consists of three data chapters (Chapters Two-Four) and a literature review (Chapter Five). Below, I briefly outline each chapter:

Chapter Two: Potential impacts of climate change on habitat suitability for the Queensland fruit fly (Sultana et al. 2017, Scientific Reports).

This chapter focuses on Queensland fruit fly (*B. tryoni*, Qfly) as it is the most economically damaging insect pest of Australia's horticulture industry. As such, its management is a key priority for plant protection and biosecurity in Australia. Within this chapter, I used the species distribution model, Maxent, to assess how climate change may impact the distribution of suitable habitat for Qfy across a range of plausible climate scenarios. I then assessed the extent to which the Fruit Fly Exclusion Zone (FFEZ) and other Australian horticultural areas may be suitable for Qfly in 2030, 2050 and 2070. I found that south-western Australia, northern regions of the Northern Territory, eastern Queensland, and much of south-eastern Australia are suitable for Qfly under current and future climate scenarios. My results also provide an initial estimate of the potential exposure of Australia's horticulture industry to Qfly as climate changes, highlighting the need for long-term vigilance across southern Australia to prevent further range expansion of this species.

Chapter Three: Impacts of climate change on high priority fruit fly species in Australia (Sultana et al. 2020 PLoS ONE)

Using newly developed code to explore the best set of predictor variables for a given species, I extended my Maxent modelling approach to the 11 native, high priority, economically important tephritid pests (*Bactrocera aquilonis, B. bryoni, B. cucumis, B. frauenfeldi, B. halfordiae, B. jarvisi, B. neohumeralis, B. musae, B. tryoni, Ceratitis capitata,* and *Zeugodacus cucumis*) that are present within Australia. A number of these species are highly polyphagous and pose threats to Australia's horticulture industries, as well as to backyard growers. As such, control of these fruit flies is very important for the viability of Australian horticulture, monitoring to demonstrate pest freedom, and quarantine and trade restrictions. Based on projections of current and future climatically suitable habitat, I identified 'hotspot' regions suitable for multiple pest species, and highlighted areas at risk of pest range shifts, to guide Australia's horticulture industries in development of effective monitoring and management strategies.

Chapter Four: Estimating the current and future risk of exotic fruit fly species establishing in Australia (for submission to Scientific Reports)

In Chapter Four, I assessed the relative risk of 19 exotic tephritid species that are currently absent from Australia. These species have been economically damaging to horticulture industries elsewhere, and hence pose a threat should they gain entry to Australia. I assessed the relative likelihoods of establishment of these 19 species, based on the proportion of the continent with similar climate to each species' known range, the distribution of commercial host plants within Australia, and a key arrival pathway (i.e. the movement of people dispersing from host countries). I then assessed how estimates of relative risk may change as a result of climate change.

Chapter Five: The impact of climate change on tephritid pests

In this chapter, I discuss more broadly the issue of climate change and tephritid pests. I present a literature review of these species, how they may respond to climate change (from range shifts to phenological changes and adaptation), key knowledge gaps, and consequences for horticulture industries worldwide.

Chapter Six: Thesis Discussion

This chapter summarises my PhD, including key findings, limitations and future directions for research.

As each chapter of this thesis is written for a specific scientific journal, there is some overlap in the discussion of key concepts and, in places, the methods and datasets used. This is inevitable and necessary for each chapter to function as a stand-alone paper. In addition, as with most contemporary scientific research, my chapters were the result of collaborations that I developed throughout my candidature. The contribution of co-authors is stated in the thesis declaration.

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CHAPTER TWO

Potential impacts of climate change on habitat suitability for the Queensland fruit fly

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Abstract

Anthropogenic climate change is a major factor driving shifts in the distributions of pests and invasive species. The Queensland fruit fly, *Bactrocera tryoni* Froggatt (Qfly), is the most economically damaging insect pest of Australia's horticultural industry, and its management is a key priority for plant protection and biosecurity. Identifying the extent to which climate change may alter the distribution of suitable habitat for Qfly is important for the development and continuation of effective monitoring programs, phytosanitary measures, and management strategies. I used Maxent, a species distribution model, to map suitable habitat for Qfly under current climate, and six climate scenarios for 2030, 2050 and 2070. My results highlight that south-western Australia, northern regions of the Northern Territory, eastern Queensland, and much of south-eastern Australia are currently suitable for Qfly. This includes southern Victoria and eastern Tasmania, which are currently free of breeding populations. There is substantial agreement across future climate scenarios that most areas currently suitable will remain so until at least 2070. My projections provide an initial estimate of the potential exposure of Australia's horticultural industry to Qfly as climate changes, highlighting the need for long-term vigilance across southern Australia to prevent further range expansion of this species.

Keywords: biosecurity, climate change, horticulture, pests, Queensland fruit fly, species distribution models

Introduction

The Queensland fruit fly (Qfly), *Bactrocera tryoni* Froggatt, is the most devastating pest of Australia's $9 billion p.a. horticulture industry. Endemic to north-eastern Australia, its range expanded southwards following the planting of exotic horticultural crops (Birch 1961). Populations now span eastern Australia from the Cape York Peninsula in far north-east Queensland, through New South Wales (NSW) and into the southern state of Victoria where its range has been reported to be restricted by low precipitation and temperature to the west and south, respectively (O'Loughlin et al. 1984). Qfly has also achieved serious pest status in the north of the Northern Territory (Meats 1981), although it is unclear whether these populations consist of Qfly or a fertile hybrid with *Bactrocera aquilonis* (Yonow and Sutherst 1998). In the west, the climate of Perth and surrounds are suitable for Qfly (Horticultural Policy Council 1991) with outbreaks occurring during 1989–1990 (Sproul et al. 1992). Although this resulted in an extensive and successful eradication campaign, several incursions have occurred since (Sproul et al. 2001). Within urban South Australia, Qfly outbreaks have occurred due to the entry of infested fruits from other states (Maelzer 1990). Until recently, Tasmania was the only state where Qfly outbreaks were not known (Holz et al. 2010). As such, it has long been recognised for 'area freedom' from fruit flies. With area freedom, crop production costs are lower as produce does not require costly disinfestation procedures before being exported (Sutherst et al. 2000), and this adds considerably to the value of the state's horticultural industry (Holz et al. 2010). However, in early 2018, incursions of Qfly larvae were detected in two regions of Tasmania: the Furneaux Group of islands, and the other at Spreyton in the north of mainland Tasmania. Traced to infested imported fruit, these events led to a formal declaration of outbreaks, followed by the largest biosecurity response in Tasmania's history (Blake 2019).

Qfly attacks more than 100 native and introduced host plant species (Hancock et al. 2000), including citrus, pome and stone fruits, berries and tropical fruits, and 'fruiting vegetables'. The economic costs of this pest are considerable. Abdalla et al. (2012) estimated the annual cost of pre-harvest bait and cover spraying over the period 2006–2009 to be ~$48 million, while post-harvest treatments (which may include chemical fumigants, temperature treatments, or irradiation, Hallman 1999) necessary to transport produce interstate exceeded $22 million p.a. Even with these treatments, production losses in fruit fly endemic regions range from 0.5–3% (Abdalla et al. 2012). The above figures do not include costs to backyard growers (which in the absence of eradication programs could result in 80% of the value of backyard fruit production being lost, van Velsen 1987), costs of restricted access to domestic or international markets, and flow-on costs to related industries, such as food retailers and processors, or the wine industry (Abdalla et al. 2012).

Given the costs of Qfly and other fruit flies to the horticultural industry, the Tri-state Fruit Fly Exclusion Zone (FFEZ) was established in 1994, spanning the major fruit growing regions of south-western New South Wales, north-western Victoria and south-eastern South Australia (Dominiak and Daniels 2012). In an endeavour to keep the FFEZ free of fruit flies, and thereby maintain high value markets, there were stringent legislative controls on the transport of fruit and vegetables into this region. However, in 2010–2011, the FFEF was subjected to the wettest two-year period on record, and outbreaks occurred in the NSW and Victorian parts of the FFEZ. Control and eradication measures became technically unfeasible and economically unsustainable. By August 2013, the legislation supporting the FFEZ was withdrawn in NSW and Victoria, and the Zone ceased to be a trade zone (Dominiak and Mapson, 2017). The Sunraysia Pest Free Area stills exists in the northwest corner of the FFEZ, although this zone is currently suspended.

As with other insects, the distribution, abundance and development rate of Qfly are strongly influenced by climate. In particular, there is a strong positive correlation between summer rainfall and Qfly abundance (Bateman 1968, Bateman 1972, Yonow and Sutherst 1998), with O'Loughlin (O'Loughlin 1964) noting that abundance increases significantly when summer rainfall exceeds 170 mm per month. Without rainfall, the fecundity of adult females declines, mortality of larvae and newly emerged adults increases, and there may be markedly diminished emigration to nearby regions (Bateman 1972). Temperature also influences the distribution and development of Qfly (Bateman 1972). The critical lower temperature, below which individuals cannot move spontaneously, is ~2°C, and although adults may survive at temperatures of 38–40°C (Bateman 1968, O'Loughlin et al. 1984), immature stages are more vulnerable to such extremes (Meats 1984).

Given the dependence of Qfly distribution and abundance on climate variables, there is concern that as climate change intensifies, warmer temperatures and changes to precipitation patterns will facilitate the spread of populations southward and into Tasmania (FAO 2006). There is also the potential for more frequent outbreaks to occur within the former FFEZ and in other Australian horticultural regions.

Previous studies using the semi-mechanistic species distribution model, CLIMEX, have estimated the potential for Qfly to undergo increases in population sizes and range expansion as a result of climate change (Yonow and Sutherst 1998, Sutherst et al. 2000, Holz et al. 2010). In particular, warmer winters may increase the survival and development rates of Qfly, resulting in greater population numbers in spring (Sutherst et al. 2000). While highly useful in furthering our understanding of climate impacts on Qfly, these publications were either restricted in geographic scope (e.g. to Tasmania, Holz et al. 2010) or are now somewhat dated, as the development of climate models and greenhouse gas concentration pathways has advanced considerably since their publication, as has the availability of data, the sophistication of modelling tools, and spatial resolution of analyses. As such, here I employ the species distribution model (SDM) Maxent to conduct a continent-wide assessment of the potential impacts of climate change on Qfly. Maxent is a correlative SDM that has been used extensively to assess the distribution of suitable habitat for a broad range of pest and invasive species (Kumar et al. 2014a, Aguilar et al. 2015). Our goals are to assess how climate change may impact the distribution of suitable habitat for Qfly, across a range of plausible climate scenarios. Furthermore, I assess the extent to which the former FFEZ and other Australian horticultural areas may be suitable for Qfly in 2030, 2050 and 2070. Our study provides essential foundations for a broad understanding of the potential exposure of Australia's horticultural industry to Qfly incursions in the future.

Methodology

Species data

I obtained occurrence data for Qfly from four main sources: the Atlas of Living Australia (ALA; http://www.ala.org.au, accessed 22th December, 2016), the Australian Plant Pest Database (http://www.planthealthaustralia.com.au/resources/australian-plant-pest-database, accessed 15th March, 2017), existing literature, and trap data. ALA is Australia's largest digital database of species occurrence records, containing information from a wide array of data providers including Australia's major museums and government departments. Before downloading data from ALA, I applied filters to restrict records to those that were resolved to species-level, dated after 1 January 1950, contained geographic coordinates, and were not flagged by ALA as 'environmental outliers'. APPD is a national, secure database of pest and plant pathogen specimens held within herbaria and insect collections across Australia. Records from ALA and APPD primarily represent ad hoc collections, and so were supplemented with records from specimens collected in fruit fly traps managed by various state government departments (New South Wales Regional Pest Management, Biosecurity and Food Safety; Biosecurity Queensland and the Queensland Department of Agriculture and Fisheries; Department of Economic Development, Jobs, Transport and Resources, Victoria; and Primary Industries and Regions South Australia (PIRSA)). Trap data from these sources were collected at different periods from 1996 to 2017. To reduce environmental bias due to spatially autocorrelated sampling, I reduced trap data such that pairs of points were separated by at least 10 km. I also obtained occurrence data from previous studies (May 1963, Drew et al. 1982, Osborne et al. 1997, Royer and Hancock 2012) including state government databases. After filtering/thinning, a total of 1057 unique localities (i.e. 1 x 1 km grid cells) remained.

Current habitat data

For current climatic conditions (1950–2000), I downloaded 19 'bioclimatic' variables from the WorldClim database (Hijmans et al. 2005) (http://www.worldclim.org/) at a spatial resolution of 30 arc-seconds. I assessed pairwise correlations among these variables and generated three sets of variables with Pearson correlation coefficients having absolute values <0.8. I supplemented the climate variables with data on soil characteristics, available from the CSIRO data access portal (https://data.csiro.au, accessed 28th February, 2017). These variables were developed by Viscarra Rossel & Chen (2011) from a principal *components* analysis of visible and near infrared soil spectra, and are referred to as PC1, PC2 and PC3. They describe, respectively, the distribution of highly weathered soils, soils with large amounts of organic matter, and low relief landscapes with soils containing abundant smectite (clay) minerals (Viscarra Rossel and Chen 2011).

Finally, I developed multiple Maxent models based on different combinations of the climate and soil variables, to identify the subset that resulted in models with the highest predictive power (AUC, described below). Ultimately, I selected the following variables for final model: mean annual temperature (MAT), minimum temperature of the coldest month (TminCM), temperature annual range (TAR), precipitation of the driest month (PDM) and of the coldest quarter (PCQ), and the soil variable, PC3. Hence, for the purposes of this study, I define 'suitable habitat' with respect to this combination of climate and soil variables. I note that the use of other variables may result in slightly different definitions and spatial extents of suitable habitat.

Future habitat data

Given uncertainty in scenarios of future climate, impact assessments should incorporate data from a range of climate models that are effective in simulating historical climate over the area of interest. CSIRO compared the output of 40 global climate models (GCMs) and identified a subset of eight that they recommend for use in climate impact assessments (CSIRO & BoM 2015). These eight are representative of the range of results from all 40 models, for the Australian region, and are effective in reproducing historical conditions. Of the eight climate models, six had data at a resolution of 30 arc seconds, for the Representative Concentration Pathway 8.5 (RCP8.5, Moss et al. 2010). These models, and descriptions of changes they project for mean annual temperature (MAT) and annual precipitation (AP) for 2070, are as follows. (1) CanESM2 (The Second Generation of Canadian Earth System Model) projects an extremely hot, dry future, with warming > 4°C throughout central Australia, and > 5.5°C in parts of Western Australia. AP is projected to decline throughout central and Western Australia, and increase in north-east Queensland, with few changes in the south-east; (2) ACCESS1.0 (The Australian Community Climate and Earth System Simulator) projects a hot, dry future. Warming exceeds 2.5°C across most of Australia, and > 3.5°C in central Australia. Drying is projected over most areas, including the horticultural zone in south-eastern Australia, although higher rainfall is likely in central Australia; (3) MIROC5 (Model for Interdisciplinary Research on Climate) projects moderate warming, not exceeding 3°C, and slight changes in AP with declines in north-east Queensland and south-west Australia; (4) HadGEM2 (Hadley Centre Global Environmental Model Version 2) projects a hot future with warming typically > 2.5°C, and > 3.5°C in central regions. AP is projected to increase in central Australia, and decline elsewhere including the horticultural zone; (5) NorESM1 (The Norwegian Earth System Model-Part-1) projects moderate warming, with most of the continent exceeding 2°C. Little change in AP is projected, particularly in the south-east, although there is drying in south-west WA; (6) GFDL-ESM2M (Global Coupled Climate Carbon Earth System Model Part-1) projects a hot, very dry future, with warming in central regions exceeding 3.5°C. Drying is projected across most of the continent, with AP forecast to decline more than 20% in many areas.

I downloaded scenarios from these six models for the years 2030, 2050 and 2070 from the CCAFS GCM Data Portal (http://www.ccafs-climate.org/data_spatial_downscaling/), at a spatial resolution of 30 arc seconds. Climate data were reprojected to a spatial resolution of 1 km x 1 km (Australian Albers Equal Area, EPSG: 3577) with a bilinear interpolation, using the gdalwarp function provided by the R package gdalUtils (Greenberg and Mattiuzzi 2015), in R version 3.3.3 (R Core Team 2017) (https://www.R-project.org).

Species Distribution Model

Maxent (v3.3.3k, Phillips et al. 2006) is a machine learning algorithm frequently used to assess habitat suitability for species under current and future climate scenarios, because it accommodates presence-only data and has performed well in multi-model assessments (Elith et al. 2006). Maxent produces a continuous probability surface, which can be interpreted as a relative index of habitat suitability given the predictor variables included in model calibration. Grid cells with a higher value are deemed as having greater suitability for the modelled species (Phillips et al. 2006). For detailed descriptions of Maxent, see Elith et al. (2011) and Merow et al. (2013).

Maxent requires background data, to which it can compare the environmental characteristics of presence locations. Following Ihlow et al. (2012), I generated a mask layer consisting of a 200 km buffer surrounding Qfly occurrence records, from which Maxent randomly selected 10,000 background records. Choice of background achieves a balance between fine-scale discrimination of suitable and unsuitable sites along environmental gradients, and generalisation of model predictions. In addition to comparing the predictive power of models calibrated with different sets of variables, I optimized Maxent by assessing the effect of different combinations of feature types and alternate magnitudes of regularisation on model performance. I found that Maxent performed best when product, linear and quadratic features were used, with a regularization multiplier of 1, and used this configuration to calibrate my final model. I explored the contribution of environmental variables by a) assessing their permutation importance (i.e. the change in classifier accuracy when cell values for the respective variable are randomly permuted among presence and background cells) and b) with jackknife tests, which indicate the change in model fit or performance when sequentially withholding each predictor and refitting models, and when fitting univariate models (Elith et al. 2011).

I used a ten-fold cross-validation to reduce model errors that may occur from the random splitting of data into test and training subsets. In this approach, occurrence data are split into ten subsets of approximately equal size (i.e. folds): the model is fitted using data from nine of the ten folds and tested using data from the remaining fold. This process is repeated until each fold has been used once for testing. The performance of each model was evaluated using the area under the receiver operating characteristic (ROC) curve (AUC), which describes the consistency with which a model ranks presence sites as more suitable than background sites. AUC ranges from 0 to 1 (Fielding and Bell 1997), where a value of 0.5 represents a model with discrimination ability no better than random, while a model with AUC > 0.75 is considered fair (Swets 1988).

Current and future habitat suitability

To assess current and future habitat suitability, I projected the final Maxent model onto spatial data for each of the climate scenarios. Continuous suitability predictions were then converted into binary layers indicating suitable and unsuitable habitat. The selection of a threshold for this conversion depends on the goals of the study (Wilson et al. 2005) and the extent to which false negative and false positive errors are tolerated when identifying suitable habitat (Fielding and Bell 1997). Following previous studies of pest species (Khanum et al. 2013, Aguilar et al. 2015), I selected the threshold corresponding to the 10th percentile of suitability at model-fitting presence localities. Data were then imported into ArcGIS (v 10.4, ESRI 2016). Binary layers were stacked to produce a consensus map, identifying agreement in the suitability of a grid cell across the six climate scenarios.

I obtained spatial data on the location of the former FFEZ from the Department of Primary Industries, Victoria. I also downloaded data on the primary horticultural regions of Australia, as mapped in the National Scale Land Use Version 5 (http://www.agriculture.gov.au/abares/aclump/land-use/data-download, 1 km resolution) developed by ACLUMP (Australian Collaborative Land Use and Management Program). ACLUMP contains spatial data on five types of horticultural regions (perennial; seasonal; irrigated perennial; irrigated seasonal; intensive horticultural), which span a total of 5,321 km^2. I overlaid all Maxent projections for current and future time periods onto the FFEZ and horticultural regions, to assess the extent to which these areas are likely to contain suitable habitat for Qfly. Finally, for all scenarios calculated overall range change, the proportion of current suitable habitat projected to become unsuitable ("loss") and the proportion of future habitat projected to occur in previously unsuitable areas ("gain").

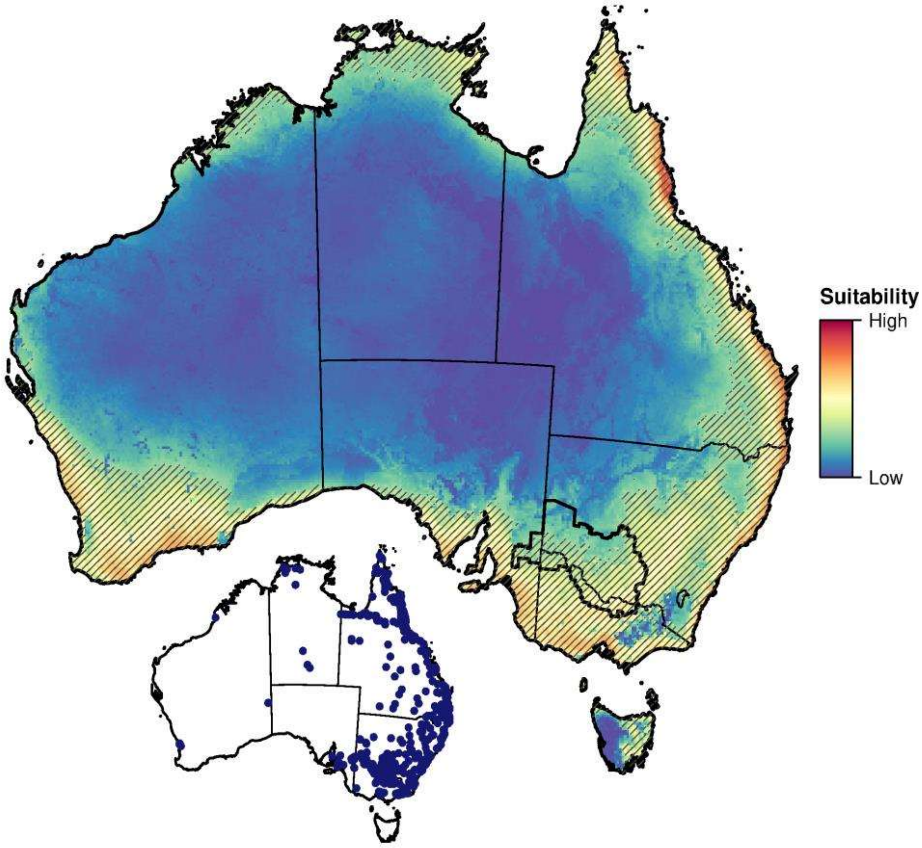

Figure 1. Current habitat suitability for Qfly modelled using Maxent (the hatched area represents regions with suitability values above the 10th percentile at training presence sites). The location of the former Fruit Fly Exclusion Zone (FFEZ) in south eastern Australia is shown as a polygon. The inset map shows the location of occurrence records of Queensland fruit fly (Qfly) from across Australia, based on specimens from natural history collections, literature and State Government-run trapping programs. Figure was created in R version 3.3.3 (R Core Team 2017) (https://www.R-project.org).

Data Availability

The datasets generated or analysed during the current study are available from the corresponding author on reasonable request. However, note that restrictions apply to data obtained from the Australian Plant Pest Database and Australian State Government Departments, which were used under license for the current study.

Results

Across the ten cross-validation iterations, the average test AUC was 0.772 (SD 0.024). The most important variable was TminCM (36.5%), followed by MAT (33.3%) and PDM (14.9%). The remaining variables contributed < 10% each to the model.

My model suggested that approximately 23% of Australia is currently suitable for Qfly. Highly suitable habitat occurs along the east coast of Queensland and New South Wales, Victoria, southeastern South Australia, and southwestern Western Australia. Coastal zones of northern Western Australia, the Northern Territory and the eastern half of Tasmania have moderate suitability, while the arid/semi-arid zones of Western Australia and the Northern Territory are unsuitable (Figure 1). Presently, ~64% of the FFEZ, spanning 120,589 km^2 across the southeast of the zone, is suitable for Qfly (Figure 1). Of the 5,321 km^2 of land throughout Australia classified by ACLUMP as horticultural, ~97% is currently suitable for Qfly.

Projections of climate change-driven shifts in habitat suitability

The geographic extent of suitable habitat is projected to decline by 2030, by an average of 18.5% across the six scenarios (SD 10.0%), although as the century progresses, gains in new habitat may exceed losses under some scenarios (e.g. see NorESM and MIROC in Figure 2). By 2070, the extent of suitable habitat is projected to be slightly larger, on average, than at present (mean 1.2%, SD 21.9%). However, there are considerable differences across climate scenarios. For example, under the hot/very dry scenario simulated by GFDL, total range size may decline ~35% by 2030, mostly due to contractions in the south and east, although limited gains in habitat may occur in northern Australia. Similarly, under the MIROC scenario, ~26% of current suitable habitat is projected to be lost by 2030, although by 2070, range expansions are projected to exceed losses. In contrast, few changes in overall range size are projected under NorESM (a moderate warming scenario with little precipitation change) by 2050, although by 2070, substantial westward range expansion is projected in eastern Australia.

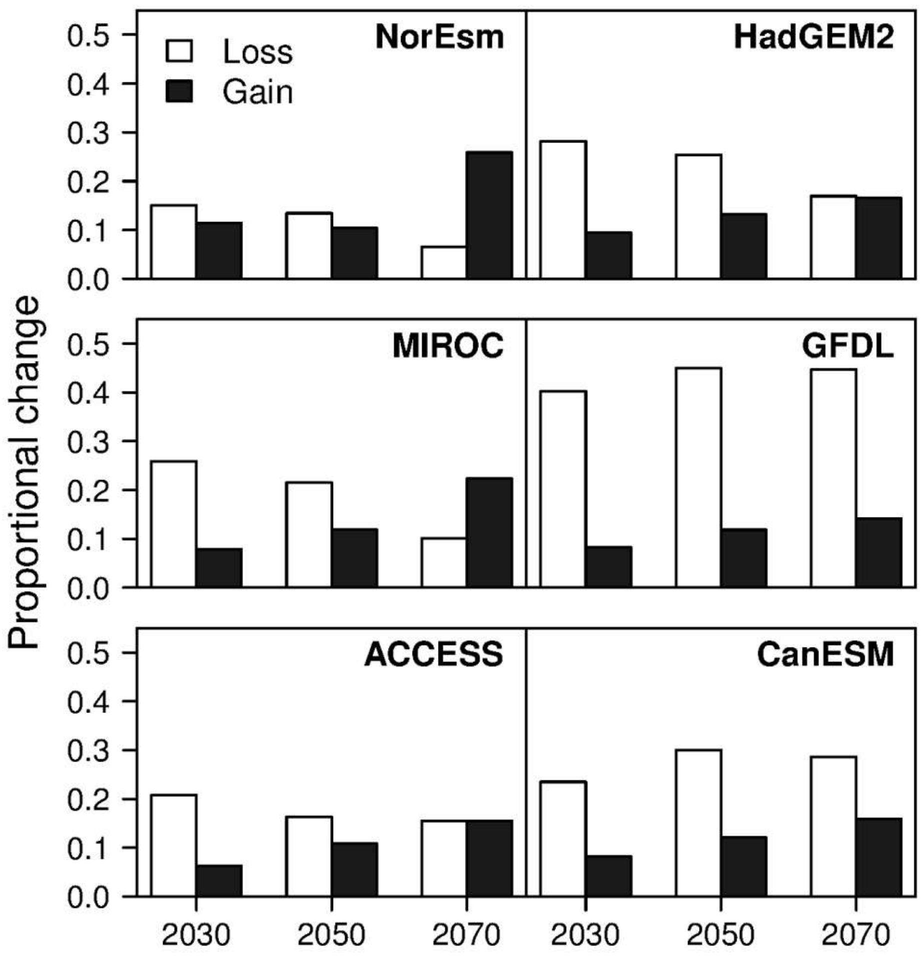

Figure 2. Projected changes in the area of suitable habitat for Queensland fruit fly, under six future climate scenarios, relative to the current period. Loss refers to the proportion of currently suitable habitat projected to become unsuitable in the future, while gain refers to the proportion of future suitable habitat that is in areas currently unsuitable.

Agreement across climate scenarios

By 2030, ~25% of Australia (i.e. ~1,900,000 km^2) is projected to be suitable for Qfly under at least one of the climate scenarios (Table 1). Due to subsequent gains in suitable habitat, this may increase to 31.7% (~2,400,000 km^2) by 2070 (Table 1). Importantly, 12.7 to 14.2% (~979,000 – 1,088,000 km2) of Australia is likely to be suitable for Qfly by 2030 and 2070, under all six scenarios. This includes most of Victoria (with the exception of high-altitude regions), much of eastern Tasmania, south-west Western Australia, eastern Queensland and the northern reaches of Australia.

Within the former FFEZ, only the south-east region is projected as suitable across five or more scenarios for all time periods (Figure 3). As the time horizon increases, however, the central and south-west regions of the exclusion zone become suitable under one to three scenarios (Figure 3).

Approximately 60% of Australia's current horticultural zones are projected to be suitable for Qfly across all climate scenarios for each time period (Figure 4). An additional 11 to 21% is projected to be suitable under 4 or 5 of the climate scenarios, for 2030 and 2070, respectively.

Table 1: Area (km^2) and % of Australia projected to be suitable for Queensland fruit fly under six future climate scenarios. That is, in the column 'N. climate scenarios', 0 refers to the area projected to be unsuitable across all six scenarios; 1 refers to the area projected to be suitable by any one of the six scenarios…6 refers to the area projected to be suitable under all six scenarios. The area of Australia is 7,687,258 km^2.

N. climate scenarios	2030 km^2	2030 (%)	2050 km^2	2050 (%)	2070 km^2	2070 (%)
0	5,767,276	75.02	5,755,445	74.87	5,252,171	68.32
1	321,497	4.18	205,527	2.67	429,639	5.59
2	125,806	1.64	147,398	1.92	192,653	2.50
3	111,207	1.44	145,441	1.89	168,931	2.19
4	140,535	1.82	222,494	2.89	303,480	3.94
5	241,687	3.14	215,993	2.81	251,669	3.27
6	979,250	12.74	994,960	12.94	1,088,715	14.16

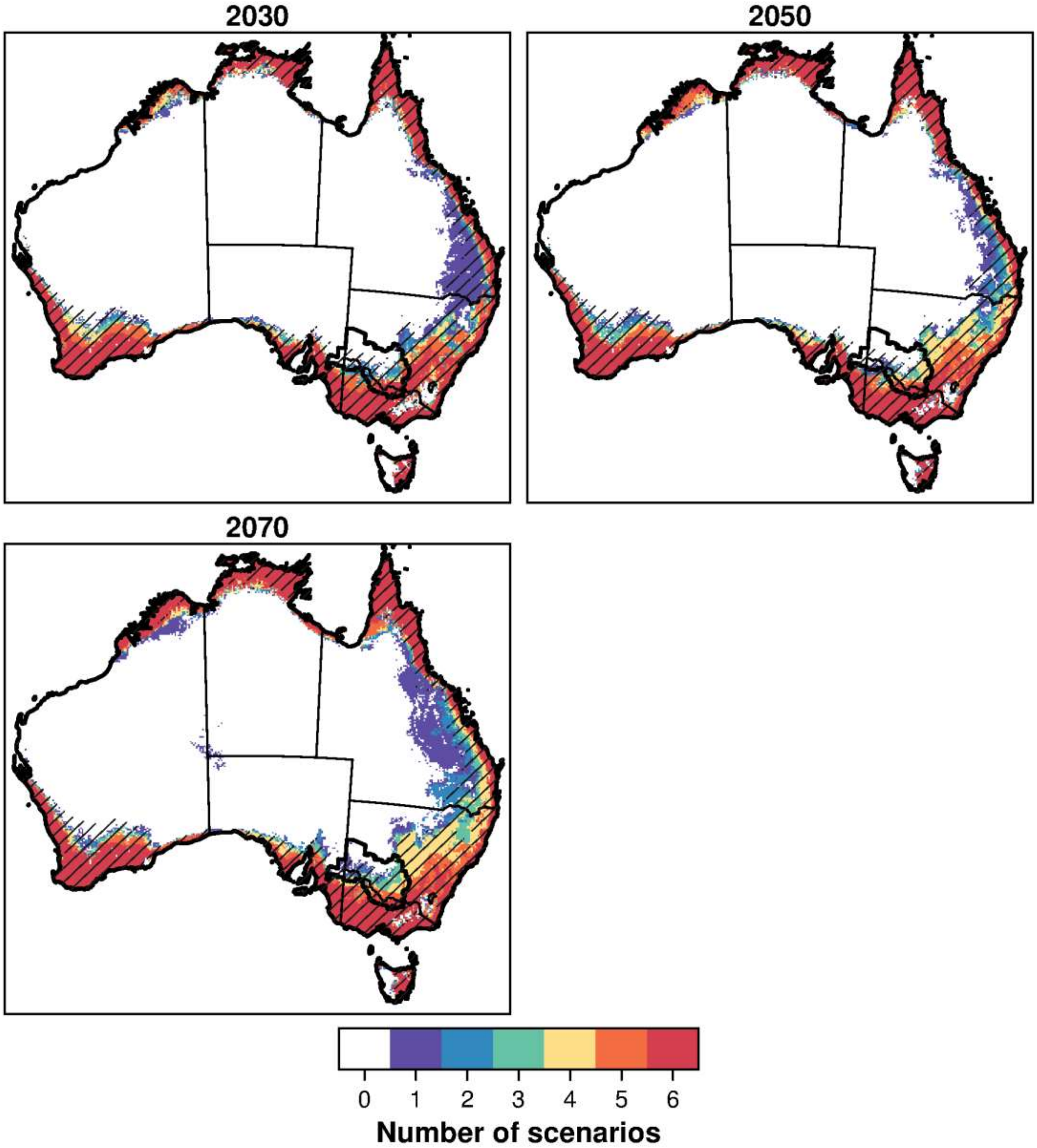

Figure 3. Agreement in the suitability of habitat for Queensland fruit fly across six climate scenarios for 2030, 2050 and 2070. Suitability was modelled with Maxent, and thresholded using the 10th percentile training presence. Colours indicate the number of climate scenarios under which habitat is predicted to be suitable. The hatched area represents regions projected as suitable for the current period. Figure was created in R version 3.3.3 (R Core Team 2017) (https://www.R-project.org).

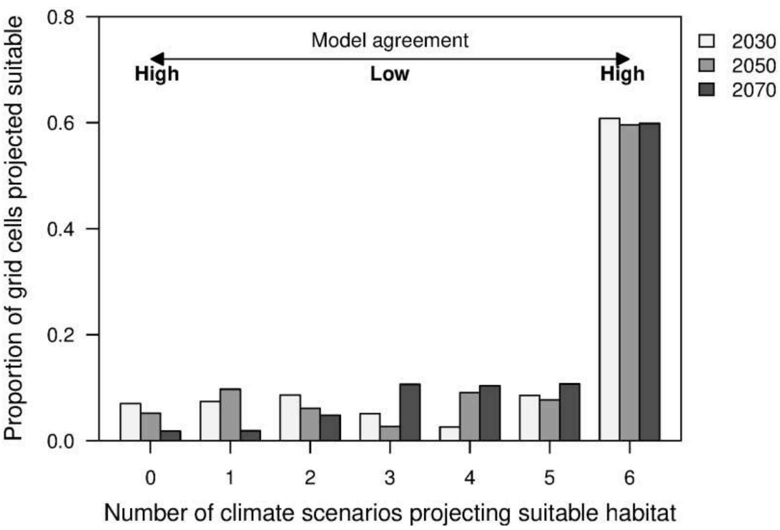

Figure 4. The proportion of grid cells that are suitable for Queensland fruit fly, and in which the primary land use is horticulture. Shown are six future climate scenarios for three time periods (2030, 2050, and 2070).

Discussion

My study revealed substantial consensus across climate scenarios that south-eastern and south-western Australia will remain suitable for Qfly, until at least 2070. Similarly, eastern Tasmania, an island state currently free of Qfly, was classified as containing substantial areas of suitable habitat under both current climate and all future climate scenarios. Depending on which climate scenario eventuates, there is also the potential for large swaths of inland Queensland to become suitable by 2070. While the level of threat that Qfly may pose to the FFEZ varies with climate scenarios, the south-eastern regions of the FFEZ are likely to remain suitable across all scenarios, as are most of Australia's current major horticultural regions. However, the northwest FFEZ is projected to be unsuitable until at least 2070.

Climate is considered ultimately responsible for determining the geographic distribution of Qfly (Yonow and Sutherst 1998). According to my model for this species, the minimum temperature of the coldest month, mean annual temperature, and precipitation of the driest month are the variables with the greatest influence on suitability. This reflects known drivers of Qfly distribution. For instance, Muthuthantri et al. (2010) reported that many subtropical sites in Queensland are marginal for Qfly breeding and general activity in winter. Similarly, the southern extent of Qfly is limited by winter temperature (Meats 1981). In Melbourne, Qfly pupae do not generally survive winter months (O'Loughlin et al. 1984). Hence, climate change driven increases in temperature of only 1–2°C may substantially elevate the threat that Qfly poses to the horticultural industry in southern Australia (Sutherst et al. 2000).

As climate changes, increases in temperature will affect the costs of Qfly management and losses incurred by growers. Sutherst et al. (2000) estimated that the cost to control Qfly within the FFEZ would increase by 24%, 33% and 83% for a 0.5°C, 1.0°C and 2.0°C temperature increase, respectively, while for growers from Qfly endemic regions in Queensland control costs may increase by 42%, 47% and 82% under each of these scenarios. Among South Australian growers, expenditure on insect control and disinfestation was projected to increase 34%, 63% and 114% for the three temperature scenarios, while the cost of management in Victoria may increase by 65%, 92% or 247% (Sutherst et al. 2000). However, these figures were based on costs associated with spraying and disinfestation of pests. In 2011, the Australian Pesticides and Veterinary Medicines Authority substantially restricted the permitted usage patterns of insecticides used to control Qfly and other fruit pests, due to concerns about toxicity (Australian Pesticides and Veterinary Medicines Authority 2011). Pre-harvest use of organophosphate compounds, such as dimethoate and fenthion, was suspended or greatly reduced, while the post-harvest use of these chemicals was strictly restricted to a subset of fruits (Australian Pesticides and Veterinary Medicines Authority 2012). Consequently, other approaches to controlling Qfly outbreaks, such as sterile insect techniques, are now being explored. Given that a large extent of Australia’s current horticultural production regions will remain suitable for Qfly as climate changes, my results indicate a need for research and development into monitoring, control, and eradication tools. I point out, however, that my analysis does not consider geographic shifts in horticultural zones that may occur due to climate change.

Comparisons with other studies

In general, my results are in agreement with those of Sutherst et al. (2000), who also predicted that Qfly will continue to pose a serious threat to the horticultural industry, particularly in southern Australia, as climate changes. As with CLIMEX (Yonow and Sutherst 1998), Maxent projects northern regions of the Northern Territory, far north Queensland and eastern Queensland, as well as south-west Western Australia and southern South Australia, to be suitable for Qfly. Further, my model indicates that the southern region of the FFEZ is also suitable for Qfly, although Yonow and Sutherst’s (1998) model suggests this to be of marginal suitability. The primary difference between my projections and those of Yonow and Sutherst is that Maxent classifies much of Victoria and the eastern half of Tasmania as currently suitable whereas these areas were projected unsuitable by CLIMEX. However, there have been major outbreaks of Qfly in Victoria this century (Ha et al. 2010) and it is clear that Qfly populations can now persist there, likely due to climate change-related warming and, potentially, increases in the level of cold tolerance of adults (Kalang et al 2008, as reported in Holz et al. 2010).

More recent CLIMEX projections for Tasmania were undertaken by Holz et al. (2010). These results also contrasted with my model. Again, CLIMEX projected that permanent Qfly populations would not be able to establish in this state, although transient populations that may last several generations could occur if the fly was introduced into certain areas. The authors point out that because climate varies substantially across short distances in Tasmania, the spatial scale of modelling studies can influence results. Analysis was conducted at a resolution of 1 km, an order of magnitude finer than Holz et al. (2010), who used grid sizes of 0.1 and 0.5 degrees.

Both Holz et al. (2010) and Sutherst et al. (2000) projected that climate suitability for Qfly in Tasmania and across southern Australia, respectively, will increase as climate change intensifies. My models also indicate that these regions will be suitable until at least 2070, irrespective of the climate scenario. In particular, my results concur with Holz et al.'s (2010) projection of increased risks along the north and east coastlines of Tasmania. I note, however, that Sutherst et al.'s (2000) models generally projected a far greater extent of mainland southern Australia to be suitable under current and future conditions than my model. In some respects, it is difficult to compare my results with those of Sutherst et al. (2000) who included irrigation when formulating their model. It is possible that my model's projections of future habitat suitability for urban and horticultural areas may be altered should irrigation be incorporated. These two studies also utilised different baseline climate data sets and spatial resolutions (50 km versus 1 km).

Finally, Maxent and CLIMEX offer two very different approaches to modelling habitat suitability. As a correlative model, Maxent generates predictions based on statistical relationships between occurrence patterns and environmental data. In contrast, CLIMEX, a semi-mechanistic model, can be calibrated by setting parameter values that describe the species' response to temperature and moisture either based on physiological data or inferred from the species' known distribution (Yonow and Sutherst 1998). A number of previous studies have compared the output of Maxent and CLIMEX for both invasive and non-invasive species. Most of these studies found the models to generate similar geographic extents of suitable habitat (Lozier and Mills 2011, Kumar et al. 2014a, Kumar et al. 2015, Kumar et al. 2016). For example, Kumar et al. (2015) used both models to project the global distribution of the codling moth, *Cydia pomonella*, a major pest of pome and stone fruits. Both models' projections reflected the current known distribution of the moth, although Maxent projected marginally suitable habitat to cover a greater geographic extent than CLIMEX projected. In contrast, Kumar et al. (2014b) found that Maxent provided a more realistic model of the western cherry fruit fly, *Rhagoletis indifferens*, compared to CLIMEX, and suggested that differences in the suitability maps may have occurred due to different spatial resolutions (5 km, Maxent; 18 km, CLIMEX) and predictor variables (WorldClim, Maxent; CliMond, CLIMEX). I suggest that it would be very worthwhile to undertake a thorough comparison of projections for Qfly derived from both Maxent and CLIMEX.

Model Limitations and Uncertainties

Errors and uncertainties in SDM output may occur for a variety of reasons, including limitations in occurrence data (Veloz 2009, Syfert et al. 2013), selection of background points (Phillips 2008, Phillips et al. 2009), spatial resolution, extent of the study area, and selection of predictor variables (Guillén and Sánchez 2007). To minimise model errors, I (1) reduced the number of variables by assessing collinearity, (2) examined spatial autocorrelation and sampling bias before modelling, and (3) extracted background points from areas situated within 200 km of Qfly occurrences.

I converted continuous probability surfaces projected by Maxent to binary suitable/unsuitable maps, since this facilitates effective portrayal of model consensus. However, two types of errors occur in binary classification models. False negatives (or omission errors) occur when suitable habitat is classified as unsuitable, whereas false positives (or commission errors) are when unsuitable habitat is classified as suitable. Both can be costly when the output of models is used to support management decisions (Guisan et al. 2013). For invasive species, false negatives may translate into an underestimation of the geographic extent of suitable habitat, and hence, invasion risk. This may be particularly problematic if it results in poor decision-making (Hartley et al. 2006) such as allowing movement of goods (Pheloung et al. 1999) or the failure to establish appropriate surveillance or containment measures (Guisan et al. 2013). In contrast, false positives may result in some locations being unnecessarily monitored (Hartley et al. 2006). The relative, application-specific importance of these errors is critical when selecting a threshold value at which to convert a continuous suitability map into a binary suitable/unsuitable map. In the context of Qfly, a precautionary approach would seem warranted: incorrectly labelling suitable habitat as unsuitable is particularly problematic, since the costs associated with uncontrolled incursions are likely to outweigh the costs of inadvertently monitoring an unsuitable site. Accordingly, I assumed that areas were 'suitable' if their predicted suitability was at least as high as the 10th percentile of suitability at presence localities. This ensures that the majority of conditions currently encountered by Qfly populations are considered suitable. However, it also accommodates some degree of positional error in occurrence data and may exclude regions for which the occurrence records represent anomalies (e.g. populations that represent rare outbreaks or presences associated with transportation of goods, such as in central Australia and parts of the Northern Territory and western Queensland). Using a lower threshold increases the geographic extent of suitable habitat. For Qfly, this would result in suitability in Queensland and northern regions of the Northern Territory more closely aligning with Yonow and Sutherst's (1998) model. However, it would also extend the distribution of suitable habitat in southern Australia, resulting in greater differences with Yonow and Sutherst (1998) for this region.

The selection of environmental predictor variables to be used in an SDM should be driven by the ecology and biology of the modelled species (Porfirio et al. 2014). I used a set of general predictor variables related to soil and climate, yet other important environmental variables, such as host availability and dispersal, can influence species' distributions. To some extent, I accounted for the influence of host availability by assessing changes in suitability within mapped horticultural regions. However, our currently incomplete knowledge of these aspects of species' ecology means that including such variables remains a key challenge for modelling studies (Heikkinen et al. 2007). Hence, here I limit my focus to assessing the effects of climate change on climatic suitability.

Conclusions

My modelling projects that much of south-eastern and south-western Australia, eastern Queensland and Tasmania, as well the northern regions of Northern Territory, will likely be climatically suitable for Qfly throughout much of this century. As such, Qfly will remain a very real threat to Australia's horticultural industry and backyard growers. For those markets that depend on area freedom, climate change may also translate into uncertainty about the security of market access (Sutherst et al. 2000). My projections provide guidance on the potential exposure of Australia's horticultural industry to Qfly as a result of climate changes and highlight the need for long-term vigilance across southern Australia to prevent further range expansion of this species.

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CHAPTER THREE

Impacts of climate change on high priority fruit fly species in Australia

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Abstract

Tephritid fruit flies are among the most destructive horticultural pests and pose risks to Australia's multi-billion-dollar horticulture industry. Currently, there are 11 pest fruit fly species of economic concern present in various regions of Australia. Of these, nine are native to this continent (*Bactrocera aquilonis, B. bryoniae, B. halfordiae, B. jarvisi, B. kraussi, B. musae, B. neohumeralis, B. tryoni* and *Zeugodacus cucumis*), while *B. frauenfeldi* and *Ceratitis capitata* are introduced. To varying degrees these species are costly to Australia's horticulture through in-farm management, monitoring to demonstrate pest freedom, quarantine and trade restrictions, and crop losses. Here, I used a common species distribution modelling approach, Maxent, to assess climate suitability for these 11 species under current and future climate scenarios. These projections indicate that the Wet Tropics is likely to remain suitable to all 11 species until at least 2070, with the east coast of Australia also likely remain vulnerable to multiple species. While the Cape York Peninsula and Northern Territory are projected to have suitable climate for numerous species, extrapolation to novel climates in these areas decreases confidence in model projections. The climate suitability of current major horticulture areas in eastern Queensland, southern-central regions of New South Wales and southern Victoria to these pests is projected to increase as climate changes. My study highlights areas at risk of pest range expansion in the future, to guide Australia's horticultural industry in developing effective monitoring and management strategies.

Keywords: Tephritidae, fruit flies, species distribution modelling, climate suitability, climate change

Introduction

Tephritid fruit flies are one of the most destructive and economically significant pest insect families, attacking a wide range of fruit and vegetables. While the family contains more than 4000 species, around 350 are recognized as economically important horticultural pests (Plant Health Australia 2018) that have significant impacts on global horticultural production and market access. In Australia, the average annual value of crops susceptible to fruit flies is multi-billion ($AUD) (Plant Health Australia 2018), and the National Fruit Fly Strategy has identified 46 species as 'high priority pests' (Plant Health Australia 2008) of concern. The majority of these species are exotic to Australia, primarily found in South-East Asia and the South Pacific (Plant Health Australia 2008, 2018), and are yet to establish populations in Australia. Of the 11 species that are currently present in Australia (Hancock et al. 2000, Plant Health Australia 2008) (Table 1), seven are reported to cause significant economic losses (*Bactrocera aquilonis, B. jarvisi, B. neohumeralis, B. musae, B. tryoni*, *Ceratitis capitata*, and *Zeugodacus cucumis*) (Horticultural Policy Council 1991, Plant Health Australia 2011). Combined, these species infest a wide variety of hosts, with some (e.g. *B. frauenfeldi, B. jarvisi*, *B. neohumeralis, B. tryoni* and *Ceratitis capitata*) (Hancock et al. 2000) being highly polyphagous.

The distributions of Australia's pest fruit fly species are influenced by their climatic tolerances and the distributions of their hosts. *Bactrocera* originated in tropical regions and have their highest richness in rainforests (Drew 1989). However, over the last 100 years, as horticulture has proliferated across Australia, some species have expanded their geographic range and host breadth (Smith et al. 1988). Of the 11 high priority fruit fly species presently on the continent, three are currently restricted to north-east Queensland (*B. frauenfeldi, B. kraussi* and *B. musae*) (Royer and Hancock 2012). In contrast, the geographic range of *B. neohumeralis* (Lesser Queensland fruit fly) extends along eastern Australia, from Queensland to central New South Wales (NSW) (Hancock et al. 2000, Royer and Hancock 2012). Previous climatic analysis indicates that this species also has the potential to establish elsewhere in northern Australia (Horticultural Policy Council 1991). The remaining species have substantially wider climate tolerances, and are found across broad regions of the continent. For instance, *B. tryoni* (Qfly) ranges across much of eastern Australia, eastern Queensland and northern regions of the Northern Territory. *Bactrocera jarvisi* (Jarvis' fruit fly) extends from northwest Western Australia, across the Northern Territory to northern Queensland and the Torres Strait Islands (Horticultural Policy Council 1991, Dominiak and Worsley 2017), and, in favourable years, may spread down the east coast of Australia into northern coastal NSW (Horticultural Policy Council 1991, Dominiak and Worsley 2017). Hence, *B. jarvisi* and *B. tryoni* have overlapping geographic ranges and infest many of the same hosts (Horticultural Policy Council 1991). *Ceratitis capitata* (Medfly) originated from the Afrotropical region (De Meyer et al. 2002), and was introduced into the Perth area (Western Australia) in the late 1800s (Horticultural Policy Council 1991). Before quarantine controls were developed, this species spread to NSW, Victoria, and other parts of Australia (White and Elson-Harris 1992). However, for reasons that remain unclear, Qfly is believed to have displaced Medfly throughout most of its former Australian range (Permkam and Hancock 1994), and now Medfly is confined to Western Australia, with occasional detections in South Australia (Dominiak and Mapson 2017).

Under current climate conditions, most of these 11 fruit fly species pose threats to Australia's horticulture industries, as well as to backyard growers. As such, controlling fruit flies is imperative for the viability of Australian horticulture, necessitating in-farm management and pest treatment, monitoring to demonstrate pest freedom, and quarantine and trade restrictions (Plant Health Australia 2008, 2018). These controls, along with loss of market access, are estimated to cost Australian growers $100 million per annum (Horticultural Policy Council 1991), in addition to losses of up to $159 million per annum due to infestation of fruit and vegetable crops (Plant Health Australia 2016).

For those areas where fruit flies are found, the annual cost, as reported in 2012, of bait and cover spray, as well as post-harvest treatments, amount to $269 ha^{-1} and $62.36 tonne^{-1}, respectively (Abdalla et al. 2012), while maintaining fruit fly free areas is estimated to exceed $28 million per annum based on data from 2009-2011 (PHA 2009). However, restrictions were recently placed on the use of insecticides to control fruit flies due to concerns about toxicity (Australian Pesticides and Veterinary Medicines Authority 2011), with dimethoate and fenthion suspended or highly restricted for many horticultural crops (Australian Pesticides and Veterinary Medicines Authority 2011, Clarke et al. 2011, Dominiak and Ekman 2013). Other approaches, including Sterile Insect Techniques, are now being explored. Regardless, it has been estimated that the annual likelihood of an incursion by an exotic fruit fly species is 21% (Abdalla et al. 2012), and the annual cost of eradicating these incursions is ~$13 million (PHA 2009), with rapid responses to outbreaks being crucial for eradication success (Jessup et al. 1998). Even brief incursions can result in significant economic damage due to market access restrictions that may be imposed. Climate change is likely to alter the distribution of suitable habitat for fruit fly species and areas vulnerable to outbreaks, and this could have serious repercussions for Australian horticulture (Stephens et al. 2016).

Previous studies (Kriticos 2007, Hill et al. 2016, Stephens et al. 2016) have used the semi-mechanistic species distribution model (SDM), CLIMEX, to estimate the potential geographic distributions of several high priority fruit fly species, based on their performance along climatic gradients. While highly useful in furthering my understanding of climate impacts on fruit flies, these studies have either focused on other countries or have explored global patterns of the distribution of suitable climate (Vera et al. 2002, Kriticos 2007, Aguilar et al. 2015, Hill et al. 2016, Stephens et al. 2016). Here I assess how climate change may result in shifts to the distribution of climatically suitable habitat for the 11 high priority fruit fly species present in Australia, using the correlative SDM, Maxent (Phillips et al. 2006). This SDM has been used extensively to assess the distribution of suitable habitat for a broad range of pests and invasive species (Kumar et al. 2014a,b, Aguilar et al. 2015, Kumar et al. 2015, Kumar et al. 2016). I also highlight areas at risk of pest range shifts, to guide Australia's horticulture industries in development of effective monitoring and management strategies.

Table 1. Eleven economically-significant tephritid pest species present in Australia and their major commercial hosts. This list includes nine natives (*B. aquilonis*, *B. bryoniae, B. halfordiae, B. jarvisi, B. kraussi, B. musae*, *B. neohumeralis*, *B. tryoni* and *Z. cucumis*) and two introduced species (*B. frauenfeldi* and *C. capitata*).

Species	Common name	Geographical Range*	Major Commercial Hosts (2016/17)**
Bactrocera aquilonis (May)	Northern Territory fruit fly	Top End of the Northern Territory (NT), northern areas of Western Australia	Bell pepper, tomato, lemon, mandarin, grapefruit, apple, mango, peach
Bactrocera bryoniae (Tryon)	N/A	Torres Strait Islands, mainland Queensland, northern Western Australia, NT, NSW as far south as Sydney	Chilli, tomato
Bactrocera halfordiae (Tryon)	Halfordia fruit fly	North Queensland south to the Sydney region in NSW	Citrus
Bactrocera jarvisi (Tryon)	Jarvis' fruit fly	North-western Western Australia, NT, north-west Queensland, eastern Australia from Cape York to Sydney, NSW	Mango, peach, banana, pear, apple, pawpaw, persimmon
Bactrocera kraussi	Krauss' fruit fly	Torres Strait Islands, northeast	Grapefruit, mandarin, orange, mango,

(Hardy)		Queensland as far south as Townsville	peach and banana
Bactrocera musae (Tryon)	Banana fruit fly	Torres Strait Islands, northeast Queensland as far south as Townsville	Banana
Bactrocera neohumeralis (Tryon)	Lesser Queensland fruit fly	Torres Strait Islands, eastern Queensland, northern NSW	Mango, papaw, persimmon, avocado, banana, passionfruit, apple, apricot, plum, peach, citrus, capsicum, chilli, tomato
Bactrocera tryoni (Froggatt)	Queensland fruit fly (Qfly)	Central and Top End of NT, eastern Australia, Victoria	Mango, papaw, avocado, grapefruit, passionfruit, strawberry, peach, pear, apple, banana, persimmon, chilli, capsicum, tomato, eggplant
Zeugodacus cucumis (French) (formerly *Bactrocera cucumis*)	Cucumber fruit fly	Eastern Queensland, north-eastern NSW, NT	Cucumber, pumpkin, zucchini, squash, passionfruit, tomato, pawpaw
Bactrocera frauenfeldi (Schiner)	Mango fruit fly	Native to Papua New Guinea and surrounding islands, spread to Torres Strait Islands and northern Queensland as far south as Townsville	Mango, banana, passionfruit, citrus, chilli
Ceratitis capitata (Wiedemann)	Mediterranean fruit fly (Medfly)	Native to Africa, spread to the Mediterranean regions, Western Australia, occasional detections in South Australia and NT are eradicated.	Mango, papaw, apple, peach, pear, citrus

* Plant Health Australia 2018
** The Australian Horticulture Statistics Handbook 2017/18

Methodology

Species occurrence data

I collected occurrence data for the 11 species from five main sources: the Australian Plant Pest Database (APPD; http://www.planthealthaustralia.com.au/resources/australian-plant-pest-database, accessed 15th March 2017), the Atlas of Living Australia (ALA; http://www.ala.org.au, 22nd December, 2016), the Global Biodiversity Information Facility (GBIF, https://www.gbif.org, June, 2017 [see Supplementary Information]), trap data, and existing literature. APPD is a national digital database of plant pest and pathogen specimens held within herbaria and insect collections across Australia. It is a powerful tool for market access and emergency responses to pest incursion and supports associated research activities. ALA is Australia's largest digital database of species occurrence records, containing information from a wide array of data providers including Australia's major museums and government departments. GBIF provides similar data at a global scale. Before downloading data from APPD, ALA and GBIF, I applied filters to restrict records to those that were resolved to species-level, were dated no earlier than 1 January 1950, contained valid geographic coordinates, and were not flagged by ALA as 'environmental outliers'.

I also collected trap data from various state government departments (Biosecurity and Food Safety, Department of Primary Industries, NSW; Biosecurity Queensland and the Queensland Department of Agriculture and Fisheries; Department of Economic Development, Jobs, Transport and Resources, Victoria; and Department of Primary Industries and Regions South Australia (PIRSA)). Trap data from these sources were collected at different periods from 1996 to 2017. Finally, I also obtained occurrence data from the literature (May 1963, Smith et al. 1988, Horticultural Policy Council 1991, White and Elson-Harris 1992, Hancock et al. 2000, Gillespie 2003, Plant Health Australia 2008, Dominiak 2011, Dominiak and Daniels 2012, Royer and Hancock 2012, Royer et al. 2016, Plant Health Australia 2018).

Major commercial fruit and vegetable hosts

For each of the 11 fruit fly species, I compiled information on the major commercial hosts on which infestation has been recorded. For this purpose, I defined major fruit and vegetable host species according to the Australian Horticulture Statistics Handbook (HSHB; www.horticulture.com.au) for the year 2016/2017 (2016/17). This document consolidates horticulture statistics of interest to industry members and other stakeholders. The data contained in HSHB were derived from the Australian Bureau of Statistics, projects funded by Hort Innovation, international trade sources and horticulture industry representative bodies where available.

Climate data

For current and future climate conditions I used the bioclimatic variables available within the WorldClim database, at a spatial resolution of 30 arc-seconds (Hijmans et al. 2005) (approximately 1 km; http://www.worldclim.org). These data, based on meteorological records for the period 1960–1990, comprise 19 climatic variables, 11 of which are temperature-based while eight relate to precipitation. Combined, the data represent annual trends, seasonality, and limiting or extreme environmental conditions. Assuming that host plants are available, temperature and moisture are the key factors influencing fruit fly reproduction and survival (Bateman 1972, Clarke et al. 2011). Thus, these variables were chosen as predictor candidates based on the fruit flies' biology and ecological requirements, and similar habitat suitability studies undertaken on other insects (De Meyer et al. 2010). For each species, I identified a set of ecologically-relevant variables, with minimal collinearity, that resulted in high predictive power for the model (Beaumont et al. 2016) (described below).

When projecting future suitability, I considered a range of climate scenarios to acknowledge this important aspect of uncertainty. CSIRO recommends eight global climate models (GCMs) as being useful for Australian climate impact assessments (CSIRO & BoM 2015). Data from six of these models were available from the CCAFS GCM Data Portal (http://www.ccafs-climate.org/data_spatial_downscaling/), at a spatial resolution of 30 arc seconds. These data were developed from anomalies of the original GCM data that were statistically downscaled using a thin plate spline spatial interpolation, and then applied to the WorldClim v1.4 baseline. The GCMs included: CanESM2 (The Second Generation of Canadian Earth System Model); ACCESS1.0 (The Australian Community Climate and Earth System Simulator); MIROC5 (Model for Interdisciplinary Research on Climate); HadGEM2-CC (Hadley Centre Global Environmental Model Version 2 Carbon Cycle); NorESM1-M (The Norwegian Earth System Model-Part-1); and GFDL-ESM2M (Global Coupled Climate Carbon Earth System Model Part-1). The CanESM2 model projects a hot future with drying across central regions of Australia and higher precipitation in the north-east. The ACCESS1.0 model projects a hot and dry future across most areas of Australia, while MIROC5 projects moderate warming, with drying in the north-east and south-west but higher precipitation in central Australia. NorESM1-M projects moderate warming. HadGEM2-CC and GFDL-ESM2M project a hot future with greater warming typically in central regions.

I downloaded the 19 bioclimatic variables from these six models from CCAF, for 20-year periods centred on 2030, 2050 and 2070, for the Representative Concentration Pathway 8.5 (RCP8.5) (Moss et al. 2010). With a radiative forcing exceeding 8.5 Wm^{-2} by 2100, this is the highest of the four RCPs presented in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (Moss et al. 2010). It is also the RCP that emissions are currently tracking most closely (Peters et al. 2012). After downloading, I reprojected these data to a spatial resolution of 1 × 1 km (Australian Albers Equal Area, EPSG: 3577) via bilinear interpolation, using the gdalwarp function provided by the R package gdalUtils (Greenberg and Mattiuzzi 2015) in R version 3.1.2 (Team 2014).

Species Distribution Models

I used the machine learning approach, Maxent (v3.3.3k (Phillips et al. 2006)), to assess climate suitability for species under current and future climate scenarios. Maxent accommodates presence-only data and has performed well in multimodel assessments (Elith et al. 2006). It produces a continuous probability surface, which can be interpreted as an index of climatic suitability given the predictor variables included in model calibration. Detailed descriptions of Maxent are given elsewhere (Elith et al. 2011, Merow et al. 2013). I optimized models by assessing the effects of different combinations of feature types, of competing predictor sets deemed ecologically sensible *a priori*, and of the extent of regularization on model performance. I found that Maxent performed best when product (first-order interactions), linear and quadratic features were used, with a regularization multiplier of 1 (the default) and used this configuration to calibrate my final models.

Maxent requires background data, to which it compares the environmental characteristics of presence locations. There is flexibility for users to specify which points to use as background, as well as the number of records and the spatial extent from which they are chosen (Merow et al. 2013). Following Ihlow *et al* (Ihlow et al. 2012), I generated background points by randomly selecting 100,000 cells from terrestrial areas within 200 km of occurrence records of the target species. Background records were extracted from fine-scale discrimination of suitable and unsuitable sites along environmental gradients, and generalization of model predictions.

To assess model performance, I used five-fold cross-validation to reduce model errors that may occur from the random splitting of data into test and training subsets. The performance of each model was evaluated using the area under the receiver operating characteristic curve (AUC), which describes the consistency with which a model ranks randomly chosen presence sites as more suitable than randomly chosen background sites. AUC ranges from 0 to 1, with a value of 0.50 indicating discrimination ability no better than random, while values greater than 0.75 indicates that the model has a discriminative ability that is better than “fair” (Swets 1988). Cross-validated AUC scores were presumed to reflect the performance of a single final model for each species, which used all available data.

Following previous studies of pest species (Aguilar et al. 2015), continuous suitability scores projected by Maxent models were converted to binary layers (0 = unsuitable, 1 = suitable) using the 10th percentile training presence threshold (i.e. the value that corresponds to 10% training omission). I note that the selection of a threshold value is subjective and may vary depending upon the goals of the study (Wilson et al. 2005), thus I also provide continuous output for current climate as supplemental data (**S1-S11 Figs**). For each species, the six binary suitability grids (i.e., one for each GCM, with cells assigned 0 when unsuitable and 1 when suitable) for each time period were summed to produce a consensus map, identifying agreement about the suitability of grid cells across the six climate scenarios. Each species' consensus map was then converting to a binary map indicating whether cells were projected to be suitable under the majority of GCMs (i.e., suitable in < 4 GCMs = 0, suitable in 4 or more = 1). The resulting binary maps were summed across species to identify hotspots - grid cells suitable for multiple pest species. Finally, I compared the distribution of hotspots to that of major horticultural crops.

When projecting models, extrapolation to conditions beyond the range of the training data may be unreliable. Following Elith *et al.* (Elith et al. 2010) I constructed MESS (multivariate environmental similarity surface) maps to identify regions of extrapolation (Elith et al. 2010). By revealing areas with novel environmental conditions, MESS maps can be used as a projection mask, highlighting regions for which less confidence can be placed in projections, or as a quantitative measure of prediction uncertainty (Elith et al. 2010). I then recalculated the size of projected suitable climate with novel environments excluded.

All modelling and post-modelling analyses and calculation of statistics were performed in R version 3.1.2 (Team 2014). I used the sp (Pebesma 2005) and raster (Hijmans 2015) packages for preparation and manipulation of spatial data, the dismo (Hijmans et al. 2013) package to fit Maxent models, and custom R code for rapid projection of fitted models.

Results

Model Performance

Model performance for all species was better than random, with average cross-validated AUC ranging from 0.815 (SD = 0.05; *B. frauenfeldi*) to 0.907 (SD = 0.02; *B. neohumeralis*) **(S1**

Table).

Bactrocera aquilonis: My model suggested that climatically suitable habitat for *B. aquilonis* currently exists in the northern regions of the Northern Territory and Western Australia, as well as northern Queensland where this fly has not been reported (**S1A-1B Figs**). The variables with the highest permutation importance were precipitation of the wettest quarter (68.9%) and annual mean temperature (28.9%) **(S1 Table)**.

As the century progresses, the geographic extent of climatically suitable habitat for this species is projected to increase and expand southwards under all six scenarios, with many areas currently suitable projected to remain so until at least 2070 **(S1C-1E Figs; S3 Table)**. This includes northern Western Australia, much of the Northern Territory, and north-western Queensland **(S1C-1E Figs)**. I note, however, that climate scenarios beyond 2030 frequently contain novel conditions across the northern regions of Australian, highlighting uncertainty in Maxent projections within these areas **(S12C-12E Figs; S23 Fig)**.

Key horticultural crops for *B. aquilonis* are *Mangifera indica* (mango), *Citrus* × *paradisi* (grapefruit), *Malus domestica* (apple), *Prunus persica* (peach) and *Citrus sp.* (citrus) **(S4 Table)**. The major regions where these crops are currently grown include the Northern Territory and north-east Western Australia. These regions may remain suitable for *B. aquilonis* until at least 2070. Similarly, fruit growing regions in the Wet Tropics (north-east Queensland) are likely to increase in suitability in the future. Other major host-plant growing regions in the south and east of the continent will likely remain unsuitable **(S1 Fig)**.

Bactrocera bryoniae: Current suitable habitat for *B. bryoniae* is projected to occur along the northern and eastern coastlines **(S2A-2B Figs).** Temperature annual range and precipitation of the driest month contributed the most to the model for this species (42.2% and 27.4%, respectively) **(S1 Table)**.

By 2070, suitable habitat is projected to increase under all scenarios except GFDL-ESM2M (which projects a hot, very dry future) **(S2C-2E Figs; S2 Table)**, expanding to the southern coastlines of Victoria and Western Australia. Under 1-3 scenarios, suitable habitat is projected to shift inland in Queensland and NSW. However, the amount of habitat projected to be suitable under all six scenarios remains relatively stable from 2030-2070 **(S3 Table)**. Beyond 2030, novel conditions are primarily restricted to the north-western regions **(S13C-13E Figs; S24 Fig)**.

The major horticultural host for *B. bryoniae* is *Capsicum annuum* (chilli) **(S4 Table)**. Model indicates that key growing regions for this crop in Queensland currently contain suitable habitat for *B. bryoniae*, and this will continue to be the case until at least 2070 **(S2 Fig)**.

Bactrocera frauenfeldi: Currently, climatically suitable habitat for this species is projected to be mostly confined to Cape York Peninsula and the Wet Tropics, although there are also small areas in northern Western Australia and the Northern Territory that are classified as suitable, but from which the species has not been recorded **(S3A-3B Figs).** The most important variable in the model for *B. frauenfeldi* was precipitation of the wettest quarter (75.4%) **(S1 Table)**.

As the century progresses, suitable habitat is projected to expand under all scenarios except CanESM2 **(S2 Table)**. This scenario projects a hot, very dry future, leading to loss of suitable habitat in northern Queensland by 2050. However, the extent of suitable habitat for this species is likely to remain small, relative to other species. In addition, the far north-east of Queensland contains novel conditions, decreasing confidence that this area will be suitable as the century progresses. As with other species, the Wet Tropics is projected to remain suitable and is not a region in which the model is extrapolating.

The major crops for *B. frauenfeldi* are *Mangifera indica* (mango) and *Carcica papaya* (pawpaw) **(S4 Table)**. Major production regions in north-western Northern Territory may remain suitable for this species until at least 2070, although there is substantial uncertainty across the climate scenarios. In contrast, it is very likely that the Wet Tropics will remain suitable until at least 2070, irrespective of the climate scenario **(S3 Fig)**.

Bactrocera halfordiae: Climatically suitable habitat for *B. halfordiae* is currently found in the Wet Tropics and subtropics from north Queensland to eastern New South Wales **(S4A-4B Figs).** Precipitation of the driest month (66.8%) and annual mean temperature (32.3%) contributed most to this model **(S1 Table)**.

The geographic extent of suitable habitat is projected to vary considerably across the six climate scenarios. As the century progresses, gains in new habitat may exceed losses under some scenarios (e.g. see ACCESS and MIROC5 in **S2 Table**) while losses are projected under the CanESM2 scenario (which projects a hot future, drying across central regions and higher precipitation in the north-east), mostly due to contractions in the south and east. Across the scenarios there is consensus that lower elevation regions in the south-east will be suitable. Furthermore, MESS maps indicate little model extrapolation for this species **(S15C-15E Figs)**.

Crops in the Wet Tropics may continue to be at risk from this species, until at least 2070. However, only 1–2 scenarios project horticultural regions in southern Queensland to retain suitable climate **(S4C-4E Figs)**. Although horticultural regions along the NSW-Victorian border are currently unsuitable for *B. halfordiae,* some models project these areas to become suitable between 2050–2070 **(S4 Fig)**.

Bactrocera jarvisi: Current suitable habitat for this species is projected to be mostly confined to northern Western Australia, the Top End of the Northern Territory, and eastern Australia from Cape York to NSW **(S5A-5B Figs)**. Annual mean temperature (38.0%) and precipitation of driest month (37.2%) had the highest contributions to the model for this species **(S1 Table)**. There is substantial consensus across the six scenarios that regions currently suitable for *B. jarvisi* will remain so until at least 2070 **(S5C-5E Figs; S2 Table)**. In addition, across some models, gains are projected to occur in central Queensland, Western Australia, and the Northern Territory, although model extrapolation occurs under several climate scenarios **(S16C-16E Figs; S27 Fig)**.

Comparing the distribution of suitable habitat for this fly with that of its major host crops indicates that crops currently grown in the Top End of the Northern Territory, and in eastern Australia from Cape York to New South Wales, may continue to be at risk until at least 2070. Other major host-plant growing regions in the south and west of the continent will also remain suitable for this species until 2070 **(S5 Fig)**.

Bactrocera kraussi: Suitable habitat for *B. kraussi* is projected to occur across the northern tip of Australia and northeast Queensland, as far south as Townsville **(S6A-6B Figs)**. Precipitation of the wettest quarter (75.19%) had the highest contribution to the model of *B. kraussi* **(S1 Table)**.

There is consensus across the six scenarios that the geographic extent of climatically suitable habitat may increase slightly **(S6C-6E Figs; S2 Table)**, although this is still confined to the

Wet Tropics and far north of the continent. In addition, little extrapolation to novel conditions occurs **(S28 Fig)**. Horticultural production regions in northeast Queensland may remain suitable for this species by 2070, although production regions in the south are likely to remain unsuitable **(S6 Fig)**.

Bactrocera musae: Current suitable habitat for *B. musae* is predicted from the Torres Strait Islands through to the Wet Tropics **(S7A-7B Figs)**. The most important variable in the model for *B. musae* was precipitation of the wettest quarter (78.7%) **(S1 Table)**.

Suitable habitat for this species is projected to remain restricted to the Wet Tropics and northern–most regions of the country under the climate scenarios. While there is consensus across the six climate scenarios, less confidence can be placed in projections to the north-west **(S18C-18E Figs; S29 Fig)**.

Bactrocera musae mainly attacks *Musa × paradisiaca* (banana), the production areas for which are located primarily in tropical and subtropical regions of the continent **(S4 Table)**. The major commercial growing region in the Wet Tropics is projected to remain climatically suitable for this species until at least 2070 **(S7 Fig)**.

Bactrocera neohumeralis: Current climatically suitable habitat for this species is projected to be mostly confined to the Torres Strait Islands, eastern Queensland, and north eastern NSW south to Wollongong **(S8A-8B Figs)**. Precipitation of the wettest month (47.4%) contributed most to the model for *B. neohumeralis* **(S1 Table)**.

As the century progresses, considerable differences in suitable habitat are projected across the six scenarios. For example, under the CanESM2 scenario, ~ one quarter of current suitable habitat is projected to be lost by 2030, although by 2070, range expansions are projected to exceed losses **(S2 Table)**. Similarly, under the hot, very dry scenario simulated by GFDL-ESM2M, total range size may decline by 2030, mostly due to contractions in the south and east, although limited gains in habitat may occur in northern Australia **(S8C-8E Figs; S30 Fig; S2 Table)**. There is consensus in projections of suitability across the north tips of the continent, however the MESS maps indicate that there are areas where the values of predictor variable are outside the training range, leading to model extrapolation. In contrast, greater confidence can be placed in projections of consensus along the east coast **(S19C-19E Figs; S30 Fig)**.

Production regions in eastern Queensland and north-eastern NSW will likely remain suitable for this species until at least 2070, although there is substantial uncertainty across the climate scenarios. In contrast, regions along the NSW-Victorian border and further south are projected to remain unsuitable for *B. neohumeralis* **(S8 Fig)**.

Bactrocera tryoni: Highly suitable habitat for *B. tryoni* is projected to occur along south-western Western Australia, south-eastern South Australia, Victoria, and eastern Australia from Cape York to NSW **(S9A-9B Figs)**. Coastal zones in northern Western Australia, the Northern Territory and the eastern half of Tasmania have moderate suitability **(S9A-9B Figs)**. Annual mean temperature (33.06%) and mean temperature of the coldest month (32.42%) had the highest contributions to the model for this species **(S1 Table)**.

The geographic extent of suitable habitat varies across the six climate scenarios. As the century progresses, gains in new habitat may exceed losses under some scenarios (e.g. see ACCESS1.0, MIROC5 and NorESM1-M; **S2 Table)**, while substantial declines occur under others (e.g. GFDL-ESM2M **S2 Table)**, mostly due to contractions in the south and east. Areas of consensus occur along the coastline, although less confidence can be placed in these projections for the Northern Territory and northern Western Australia due to model extrapolation **(S20C-20E Figs; S31Fig)**.

Key regions for host crops in the Top End of Northern Territory, eastern Australia from Cape York to NSW, Victoria, and some parts of Tasmania, may remain suitable for *B. tryoni* until at least 2070. Major host-plant growing regions in South Australia may also remain suitable for this species until 2070 **(S9 Fig)**.

Ceratitis capitata: Model suggests that suitable habitat for *C. capitata* exists throughout Western Australia, the Northern Territory, the east coast of Queensland to NSW and South Australia **(S10A-10B Figs)**. I note that scattered records within inland regions of Western Australia are projected as having low suitability. Annual mean temperature (47.2%) and mean temperature of the coldest month (46.2%) contributed most to the model for this species **(S1 Table)**.

Under the future climate scenarios, the geographic extent of suitable habitat is projected to increase and expand inland **(S10C-10E Figs)** with much of Victoria and Tasmania likely to be suitable. There is considerable consensus in the distribution of suitable habitat, although consensus declines in New South Wales as the time horizon increases **(S10C-10E Figs)**. As with other species, MESS maps indicate extrapolation occurs under scenarios from 2050 onwards, across the northern regions **(S21D-21E Figs; S32 Fig)**. However, my analysis indicated high consensus in suitability across the major host plant regions in Queensland, Victoria, and Western Australia.

Zeugodacus cucumis: Suitable habitat for *Z. cucumis* is projected to occur along the northern region of Western Australia and the Northern Territory, north-east Queensland, and south along the east coast to NSW **(S11A-11B Figs)**. Precipitation of the driest quarter (54.3%) and mean temperature of the coldest quarter (36.2%) had the highest permutation importance in the model for this species **(S1 Table)**.

Under future climate scenarios, the geographic extent of suitable habitat is projected to increase, expanding southward and inland, with most areas that are currently suitable projected to remain so until at least 2070 **(S11C-11E Figs)**. There is considerable variation among projections for inland regions, likely due to differences in precipitation patterns, indicating higher uncertainty about the future suitability of these regions. There is high consensus in suitability along the east coast, and while consensus is also high in the north MESS maps identify this as a region of extrapolation. There is little agreement on the suitability of inland regions of New South Wales and Queensland **(S22C-22E Figs; S33Fig)**.

Major commercial growing regions for host crops in Queensland and the Northern Territory are projected to remain climatically suitable for this species until at least 2070 **(S11 Fig)**. Other major host-plant growing regions in the south and west of the continent will likely remain unsuitable under the time periods considered in this study **(S11F Fig)**.

Future hotspots of pest fruit flies

For each time period, I stacked climate suitability maps for all species, to identify regions most likely to contain suitable climate conditions for multiple pest species (i.e. hotspots). As the century progresses, the geographic extent of climatically suitable habitat for most of the 11 species is projected to expand and shift south regardless of whether novel environments are included or excluded **(Fig 1, Fig 2 and Table 2)**. When regions containing novel climate are included, 31.6% of Australia (i.e. ~2,400,800 km²) is projected to be currently suitable for at least one of the 11 species, increasing to more than half of the continent by 2070 **(Table 2)**. However, only Queensland's Wet Tropics is likely to be suitable for all 11 species.

Figure 1. Hotspot maps of habitat suitability for the 11 fruit fly species under climate change, when novel environments are included. Hotspot maps of current and future habitat suitability for 11 fruit flies. Suitability was modelled with Maxent, and thresholded using the 10th percentile of suitability at training presence localities. These maps include projections under novel environments **(see S1-S11 for individual species maps with novel environments included)**. Colours indicate the number of species for which habitat is projected to be suitable under the majority (≥ 4) future climate scenarios. Figure was created in R version 3.3.3 (R Core Team 2017) (https://www.R-project.org/).

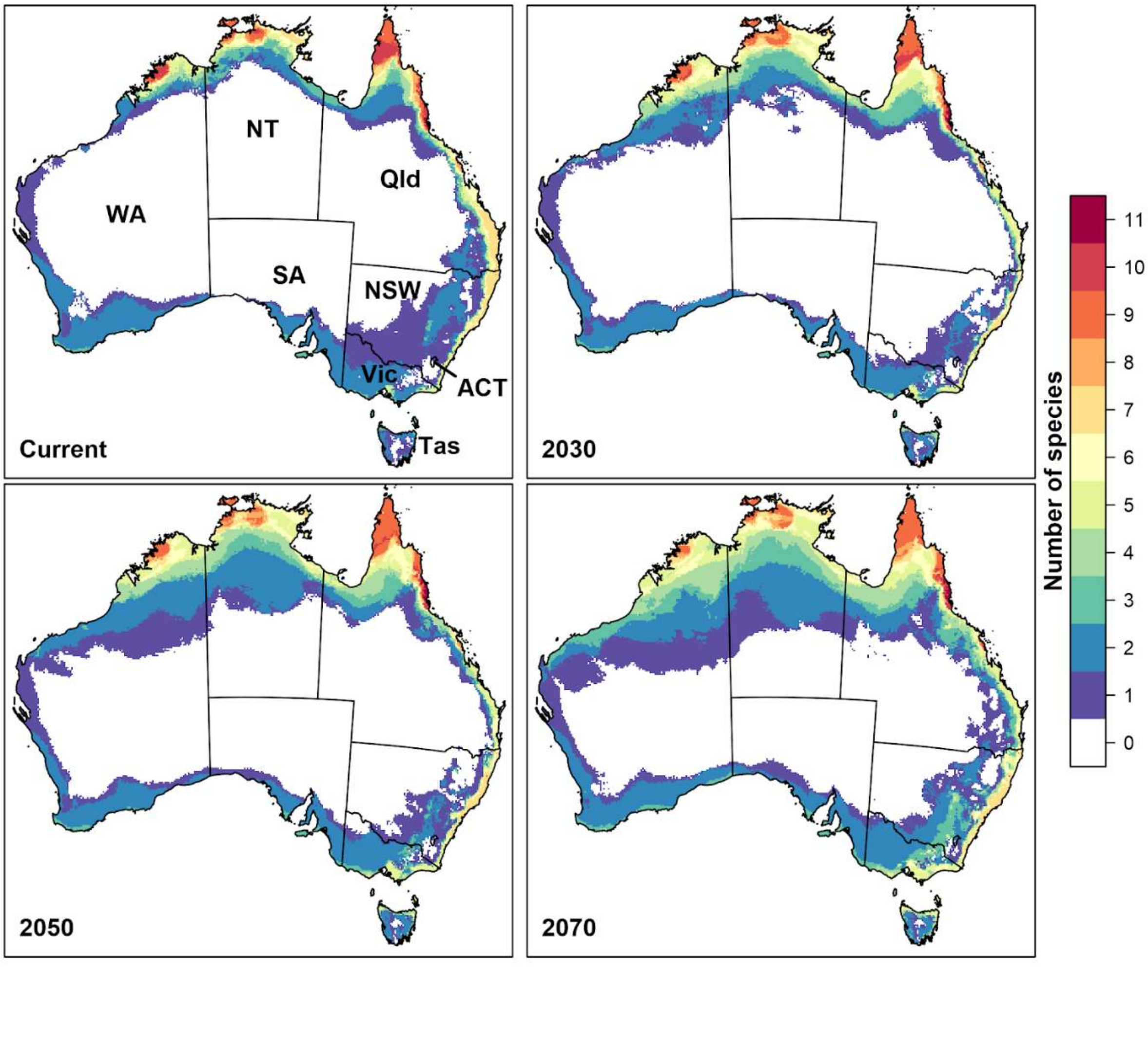

Figure 2. Hotspot maps of habitat suitability for the 11 fruit fly species under climate change, when novel environments are excluded. Hotspot maps of current and future habitat suitability for 11 fruit flies. Suitability was modelled with Maxent, and thresholded using the 10th percentile at training presence localities. These maps exclude regions containing novel environments **(see S12-S22 for individual species maps with novel environments excluded)**. Colours indicate the number of species for which habitat is projected to be suitable under the majority (≥ 4) future climate scenarios. Figure was created in R version 3.3.3 (R Core Team 2017) (https://www.R-project.org/).

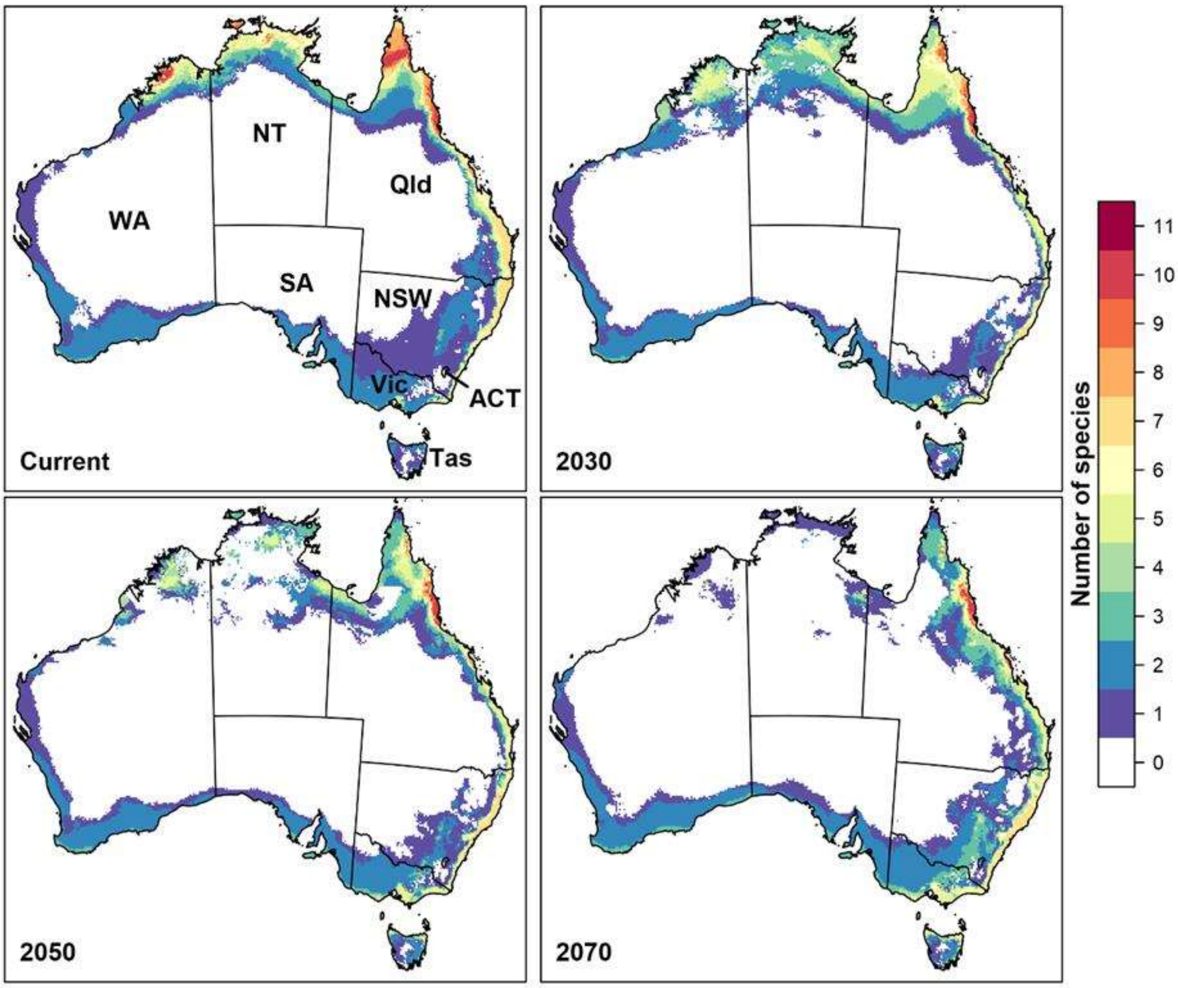

Table 2. Percentage (%) of Australia projected to be suitable for the 11 fruit fly species considered in this study, under current and future climates. This is a summary of the 'consensus' maps for each species. Values in brackets represent results when novel environments have been excluded. Each row of the table indicates the percentage of Australia projected to be suitable now, in 2030, 2050, and 2070, for *n* species, where *n* is given in the "Count" column. Thus, the first row (with Count = 0) gives the area projected to be unsuitable for all 11 species under four or more of the climate scenarios, the row with Count = 1 gives the area projected to be suitable for any one of the 11 species in at least four of the climate scenarios, and the row with Count = 11 gives the area projected to be suitable for all 11 species in at least four of the climate scenarios. Note that the number of 1 km^2 grid cells spanning Australia is 7,667,790.

	Suitable area (% of Australia)			
Count	**Current (Novel masked)**	**2030**	**2050**	**2070**
0	68.4% (68.5%)	67.5% (70.2%)	59.5% (73.6%)	47.0% (72.0%)
1	11.0% (11.1%)	9.6% (9.4%)	11.6% (9.6%)	14.6% (10.0%)
2	11.1% (11.0%)	10.5% (9.7%)	14.8% (8.8%)	17.5% (10.3%)
3	2.3% (2.3%)	3.4% (4.1%)	2.9% (3.0%)	6.5% (3.4%)
4	1.2% (1.2%)	1.9% (2.2%)	3.2% (1.6%)	4.8% (1.2%)
5	1.6% (1.8%)	2.6% (2.8%)	2.9% (1.9%)	3.9% (1.6%)
6	1.2% (1.5%)	1.9% (0.9%)	1.8% (0.6%)	2.3% (0.7%)
7	1.3% (1.3%)	0.6% (0.4%)	1.0% (0.4%)	1.2% (0.5%)
8	0.4% (0.7%)	0.4% (0.2%)	0.5% (0.2%)	0.6% (0.1%)
9	0.8% (0.3%)	1.3% (0.2%)	1.4% (0.1%)	1.4% (0.1%)
10	0.6% (0.4%)	0.3% (0.1%)	0.1% (0.1%)	0.1% (0.1%)
11	0.0% (1.3E-05%)	0.1% (0.0%)	0.1% (0.0%)	0.1% (0.0%)

When novel environments are excluded from maps, less than 30% of Australia is projected to be suitable for at least one of the species by 2070 (**Table 2**). Hence, exclusion of novel environments substantially impacts the size of suitable habitat (i.e., projections of suitable habitat frequently occur in areas with novel climatic conditions). However, extrapolation primarily occurs in northern regions of Western Australia, Northern Territory and the Cape York Peninsula, decreasing confidence in projections across these regions. From the Wet Tropics and southward, little extrapolation occurs. As such, the Wet Tropics bioregion is projected to remain suitable for 10-11 species, indicating that the major commercial host plants within this bioregion may continue to be at risk of invasion by most or all of these high priority species.

Major commercial host plant regions along the coastal strip of south-east Queensland and north-east NSW are likely to have areas that are suitable under all future scenarios for *B. bryoniae*, *B. jarvisi*, *C. capitata* and *Z. cucumis* **(S2, S5, S10 and S11 Figs)**. Under some scenarios, these regions may also be suitable for *B. halfordiae, B. neohumeralis* and *B. tryoni* **(S4, S8 and S9 Figs)**. Some major commercial host plant regions in southern NSW and

Victoria are also projected to be suitable for *B. jarvisi, B. tryoni* and *C. capitata* under all scenarios **(S5, S9 and S10 Figs)** and for *B. halfordiae, B. neohumeralis* and *Z. cucumis* under a limited number of scenarios **(S4, S8 and S11 Figs)**. Horticultural regions in Tasmania are projected as suitable for *B. jarvisi*, *B. tryoni* and *C. capitata* **(S5, S9 and S10 Figs)**.

In south-west Western Australia, major horticulture regions are likely to remain suitable for *B. jarvisi, B. tryoni* and *C. capitata*, although the latter species is currently not found in this region **(S5, S9 and S10 Figs)**. Commercial horticulture regions in northern region of the Northern Territory are also likely to be suitable for *B. jarvisi, B. kraussi, B. musae*, *B. tryoni* and *Z. cucumis* under all scenarios, and *B. frauenfeldi* under some climate scenarios.

Discussion

My study suggests that the Wet Tropics bioregion has climatically suitable habitat for the largest number of high priority tephritid pest species both now and as a result of climate changes projected to occur through to 2070. Cape York Peninsula and the Northern Territory are also likely to be vulnerable, although novel climates are projected to occur in these regions, and the extrapolation of SDMs to these conditions may be unreliable. The east coast of Australia is also likely to remain suitable for multiple species until at least 2070. As such, major horticulture regions in north-western Australia, the Northern Territory, southern-central regions of NSW, southern Victoria and north Tasmania may become increasingly suitable to high priority fruit flies. Two species, *B. tryoni* (Qfly) and *C. capitata* (Medfly), are projected to have suitable conditions in all states and territories of Australia, under all considered climate change scenarios, until at least 2070.

Over the past 30 years, numerous studies have modelled suitable habitat for both Qfly and Medfly using CLIMEX and Maxent, at various spatial resolutions (Holz et al. 2010, De Meyer et al. 2008, De Meyer et al. 2010, Sultana et al. 2017) and extents. While generally giving similar projections, a key difference is that my model projects Tasmania to be currently suitable for Qfly whereas fine scale modelling using CLIMEX indicates that it is unlikely to become suitable prior to mid-century (Holz et al. 2010).

My models for both Qfly and Medfly were driven primarily by temperature parameters, rather than precipitation. Previous studies have identified climatic constraints on the distribution of

Qfly. For example, it has been reported that Qfly pupae do not survive in the winter months in Melbourne and near Sydney (O'Loughlin et al. 1984), and adults fail to emerge later than mid-April (Muthuthantri et al. 2010). Further, many subtropical sites in Queensland are marginal in winter for Qfly breeding and general activity (Muthuthantri et al. 2010). As such, slight temperature increases associated with climate change are projected to substantially elevate the threat that this species poses to horticultural industries (Sutherst et al. 2000). For instance, using data from the late 1990s, it was estimated that annual control costs for apple growers around Adelaide may increase by between $346,000 and $1.3 million with a 0.5–2°C increase in temperature (Sutherst et al. 2000).

With the exception of Western Australia, all Australian states and territories are currently free from Medfly, with market access protocols inhibiting movement into other states (Jessup et al. 1998), and incursions met with immediate eradication programs (Dominiak and Mapson 2017). My model of current habitat indicates suitable conditions for Medfly around most of Australia's coastal regions. In addition to identifying suitability in the subtropical coastal fringe of Queensland, my model suggested that much of the low-altitude regions in the south-east, including parts of Tasmania, are also suitable. This is consistent with previous work using CLIMEX to estimate the potential distribution of Medfly (Vera et al. 2002) and Principle Components Analysis, (De Meyer et al. 2008) although projections by GARP covered a far greater spatial extent (De Meyer et al. 2008). Competition with Qfly may be responsible for exclusion of Medfly from much of Queensland (Vera et al. 2002), and similar biotic interactions may suppress the species elsewhere (Dominiak and Mapson 2017). However, Medfly may be more tolerant to low temperatures and dry summers than Qfly (Horticultural Policy Council 1991), rendering Medfly the stronger competitor in areas with these conditions. Medfly was recorded in Tasmania in the 1920s but reportedly failed to survive an unseasonably hot and dry summer (Horticultural Policy Council 1991). Due to their age, these records were not used to calibrate my model, yet my projections indicate that Tasmania continues to have conditions suitable for this species.

Bactrocera jarvisi is recognized as a pest in north-western Australia, infesting mango, guava and pomegranates (Allwood and Angeles (1979) as reported in Cameron 2006). Dominiak and Worsley (2017) concluded that the current south-eastern range limit lies north of the Queensland-NSW border (~25.5° south), while the south-western limit lies at approximately 18° south. However, previous analysis suggested that this species' current climatic range could extend into the cooler temperate areas of southern NSW, and eastern and northern Victoria (Horticultural Policy Council 1991). My models partly agree, indicating that suitable conditions currently occur along the east coast of Victoria. This species can also withstand very warm conditions, with eggs known to be more heat tolerant than those of the sympatric Qfly, surviving temperatures of 48.2°C (Cameron 2006). Given that these species infest many of the same hosts, competition is likely, hence eradication of Qfly may result in the competitive release of *B. jarvisi*, increasing the threat it poses to horticulture (Horticultural Policy Council 1991, Cameron 2006). Further, as the cultivation of *B. jarvisi* host plants expands geographically, this species may increase in abundance and extend its range, potentially becoming a major pest in north-western Australia (May 1963, Smith et al. 1988). However, across north-western Australia, and to a lesser extent the far north-east, models for most species were projected onto novel conditions, decreasing confidence in suitability estimates for these regions. In contrast, MESS maps demonstrated that extrapolation rarely occurred across eastern and southern regions, although novel interactions between climate variables cannot be ruled out.

While widespread throughout Queensland, *Z. cucumis* currently has a restricted distribution in the Northern Territory, although there is a disputed single record from northern Western Australia (Dominiak and Worsley 2018). Both Fitt (1980) and the Horticultural Policy Council (Horticultural Policy Council 1991) reported that if the cucurbit industry expands in the Northern Territory, the pest status of *Z. cucumis* may increase. However, while the species has been trapped frequently in the Northern Territory, it has not been found on cucurbits growing in this region (Smith et al. 1988). In NSW, *Z. cucumis* appears to be currently limited to regions close to the Queensland border, with rare detection as far south as Sydney (Dominiak and Worsley 2018). It has not been detected in the (former) Fruit Fly Exclusion Zone in southern NSW (Gillespie 2003). My model also estimates the southern limit of suitable climate for this species to be around Sydney. However, with climate change this may extend further southward, with parts of Victoria projected to become increasingly suitable over time, depending on the climate change scenario.

Bactrocera neohumeralis presently occurs from the western Cape York Peninsula, Queensland, south to Sydney, NSW (Hancock et al. 2000, Gillespie 2003, Royer and Hancock 2012). My model suggests that as climate changes, the range of this species may extend southward and, under some scenarios, into parts of Victoria. Previous climatic analysis also suggested that this species is well adapted to conditions on the east coast of Queensland, with large populations occurring in areas north of Townsville (Horticultural Policy Council 1991). Similar ecological characteristics are shared by *B. neohumeralis* and Qfly (Gibbs 1967), yet while Qfly is prevalent in sub-tropical and temperate areas of Queensland and NSW, *B. neohumeralis* is more prevalent in northern wet tropical areas (Drew 1989, Horticultural Policy Council 1991, Wang et al. 2003). The reason for this difference between the geographical ranges of these species is unclear, as both are polyphagous and use similar host fruits for their larval development (Gibbs 1967, Wang et al. 2003).

My model for *B. aquilonis* indicates that suitable conditions for this species are currently found in northern Queensland, although it is presently only known from north-western Australia (Drew 1989). The hosts of this species now include 40 commercial crops (Smith et al. 1988). Expansion of the range of this species, or the growth of host plant industries in north-western Australia may necessitate the development of new monitoring, control and disinfestation procedures (Cameron 2006). In addition, it has been argued that if *B. aquilonis* hybridises with Qfly, and the resulting strain may have greater potential for spread than *B. aquilonis* (Horticultural Policy Council 1991). This, in turn, would require that disinfestation procedures be developed for the hybrids (Cameron 2006).

The distribution of *B. bryoniae* ranges from the Torres Strait Islands, across northern Australia, and along the east coast to north of Sydney, NSW. My results indicate that suitable climate may exist in Victoria, i.e. south of the species' known range. However, previous studies have demonstrated that populations in northern NSW experience a marked decline in abundance through November–January (Gillespie 2003). This may be explained by a decline in the fruiting and flowering of native host trees, or seasonal climatic constraints that are not reflected in my model (Gillespie 2003), which may also explain their absence in Victoria.

Northern Queensland has the highest diversity of fruit flies in Australia, and some species with significant economic impacts are found only in this region (Royer and Hancock 2012). The distribution of *B. kraussi*, *B. musae* and *B. frauenfeldi* is limited to north Queensland (Drew et al. 1978, Hancock et al. 2000), with recent trap data suggesting that these species do not occur south of Townsville (Royer and Hancock 2012). Royer et al. (Royer et al. 2016) predicted that *B. frauenfeldi* also has suitable habitat in the Northern Territory and northern Western Australia, which is also suggested by my model. This species has expanded its range in northern

Queensland due to continued planting of hosts, such as mango and guava (Royer et al. 2016). Further increases within these horticulture industries in northern Queensland may increase the pest status of this fly (Drew et al. 1978).

Model Errors and Uncertainties

SDMs are useful for developing a broad understanding of how the distribution of suitable habitat may be influenced by climate change. However, the output of SDMs is known to be influenced by characteristics of the occurrence sample, including its size (Wisz et al. 2008), sampling bias (Syfert et al. 2013), and spatial autocorrelation (Veloz 2009), as well as the extent of the study area, selection of predictor variables (Guillén and Sánchez 2007), and selection of background points (Phillips 2008). I addressed these issues by: (1) exploring alternate settings in Maxent to optimise models and reduce overfitting that may generate unreliable estimates (Merow et al. 2013); (2) reducing the number of predictor variables by assessing collinearity; and (3) critically examining response curves.

In addition, I acknowledge that the selection of a threshold for converting Maxent's continuous output into binary data (typically defined as distinguishing between "suitable" and "unsuitable" conditions) can be subjective. A region classified as unsuitable may not be free of the pest; rather, these areas are considered less likely to support a population compared with regions above the threshold. In reality, the choice of threshold is based upon a comparison of the importance of false positives and false negatives (Franklin 2010). For invasive species, the latter may be more serious because it can result in an underestimate of the geographic extent of suitable conditions, and hence, invasion risk (Pheloung et al. 1999). This, in turn, can lead to poor decision-making and failure to establish appropriate surveillance or containment measures. As such, in this context a precautionary approach to defining a threshold, as undertaken in the present study, is warranted. However, since overprediction of suitable habitat can also prove problematic (potentially leading to ineffective allocation of monitoring resources), I provide maps of continuous (unthresholded) current suitability **(S1-11 Figs)**, permitting stakeholders to modify this threshold according to their objectives.

Sampling bias is another challenge faced when fitting correlative SDMs, particularly when incorporating data from sources of incidental observations such as museums and natural history collections (Newbold et al. 2010). As such, it is difficult to determine whether a species is observed in a particular environment because of habitat preferences or because that region has received the largest search effort (Phillips 2008, Newbold et al. 2010). For presence-background approaches to habitat modelling, a target-group background sampling strategy goes some way to handling biased occurrence samples (Elith 2013). However, while imposing environmental bias on the background counteracts similar bias in the occurrence sample, this strategy may increase the extent of novel environments to which the model must be extrapolated.

While SDMs consider exposure to climate change, species responses may also include microevolution (Salamin et al. 2010) or plasticity (Charmantier et al. 2008). As accessibility to genomic data increases, and experiments on plasticity are conducted, SDM output can be refined (Bush et al. 2016). In addition, as mean conditions change, so too will the distribution and magnitude of extremes. Presently, there has been little work undertaken to assess how different fruit fly pest species tolerate extreme weather events such as heatwaves and moisture stress.

The current analysis does not take into consideration the potential necessity for horticultural industries to shift geographically to adapt to climate change. Analysing shifts in climatic suitability for horticultural crops is complicated by my capacity to modify the environment (e.g. through irrigation), and thus was beyond the scope of this study.

To conclude, surveillance activities, pre- and post-harvest treatment, and control activities for fruit flies present a substantial cost to Australia's horticultural industries (Horticultural Policy Council 1991, Plant Health Australia 2008, 2016). My analysis highlights that the major horticultural production regions are likely to remain suitable for multiple economically important fruit fly species as climate changes. Furthermore, given that knowledge of species current distributions remains the basis for market access decisions, the potential for range shifts to occur is of critical interest to horticultural industries. Outputs from this study provide guidance to pest managers, such that they can assess pest risks and design appropriate ongoing surveillance strategies. The results of this chapter emphasize the importance of vigilance and preparedness across Australia, to prevent further range expansion of these 11 species, and underscore the need for ongoing research and development into monitoring, control, and eradication tools.

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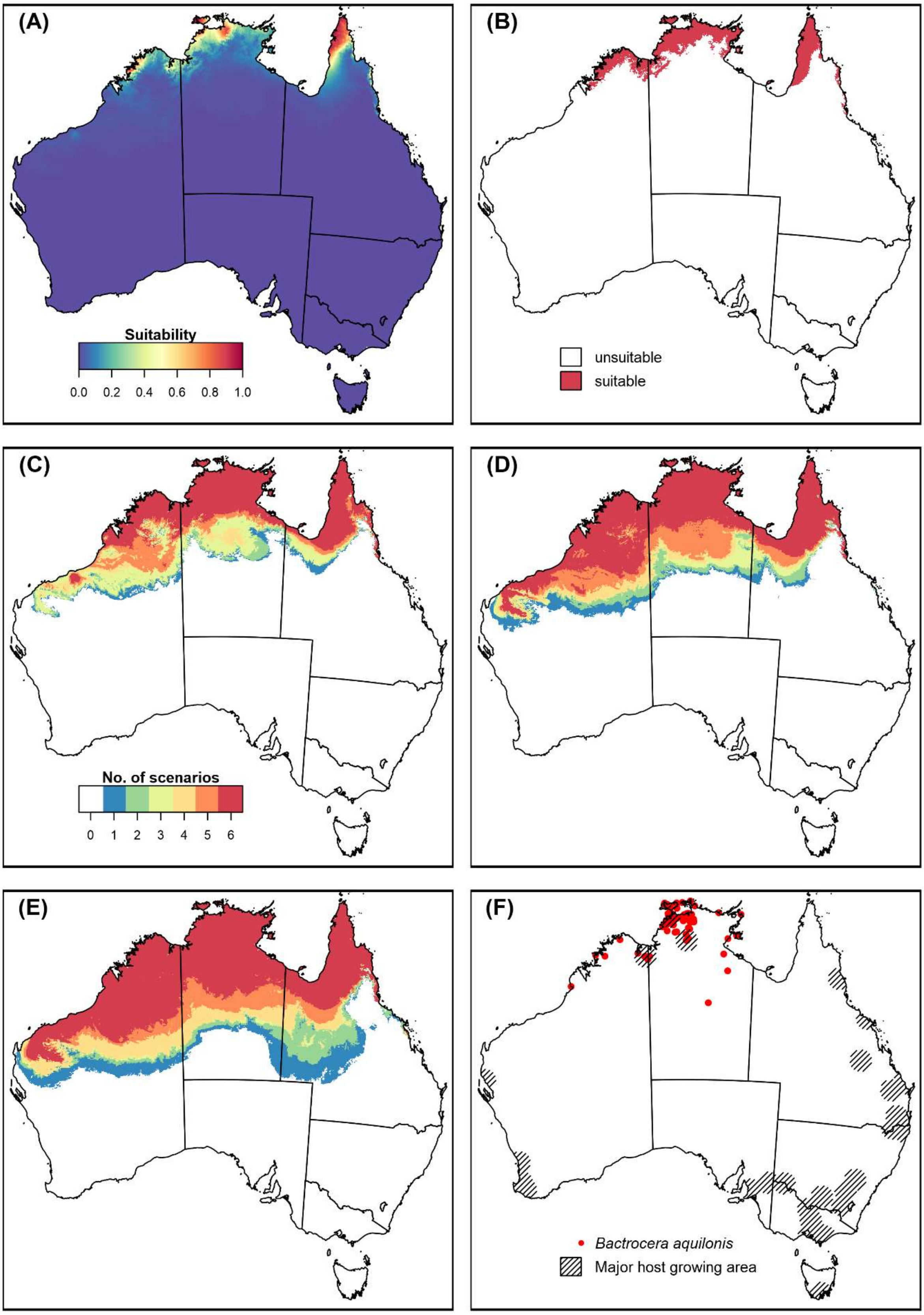
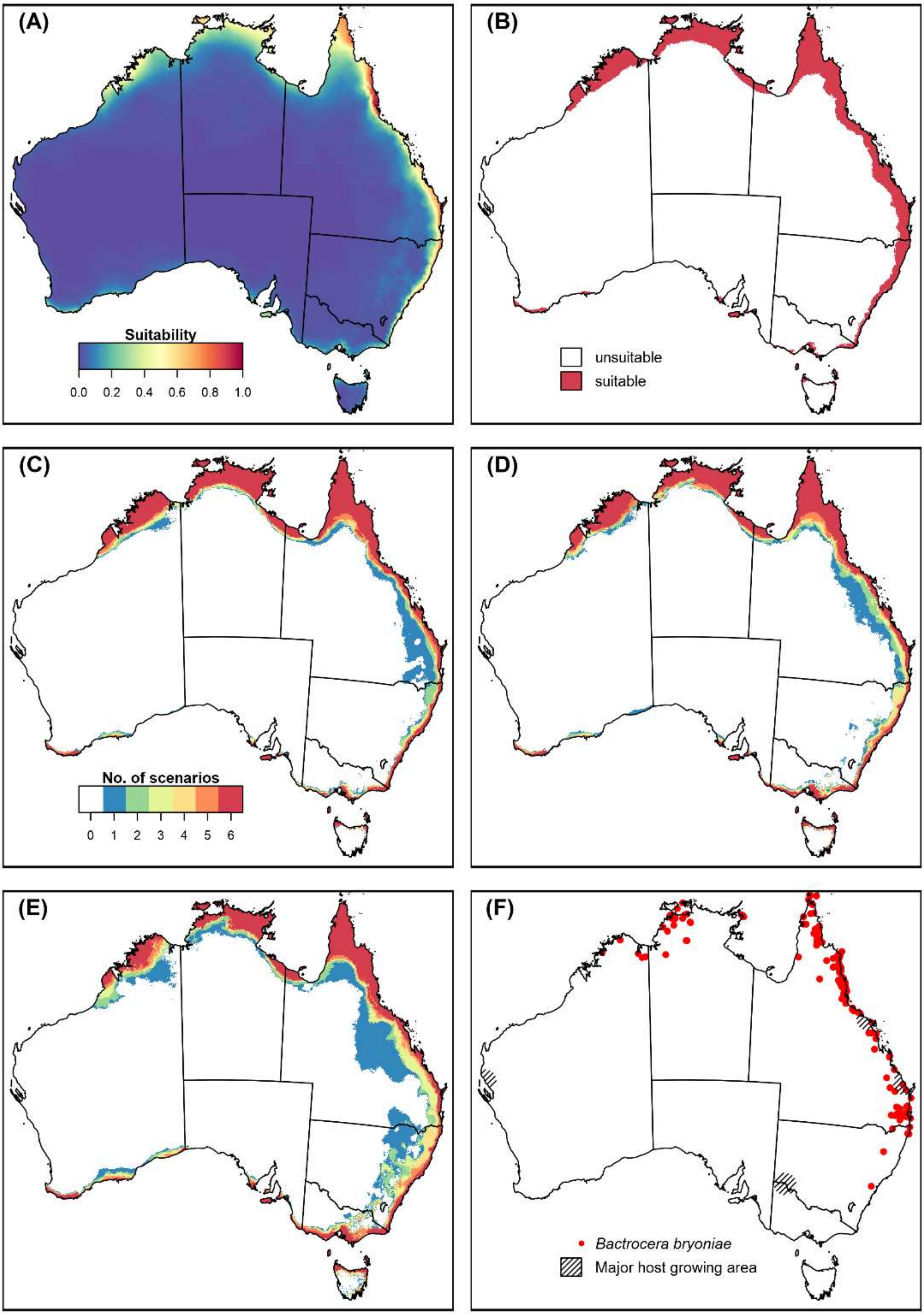
Appendix 3 Supplementary Information

S1-11 Figs. Climatic habitat suitability for 11 tephritid fruit flies under various future climate scenarios, when novel environments are included. (1) *Bactrocera aquilonis,* (2) *Bactrocera bryoniae,* (3) *Bactrocera frauenfeldi,* (4) *Bactrocera halfordiae,* (5) *Bactrocera jarvisi,* (6) *Bactrocera kraussi,* (7) *Bactrocera musae,* (8) *Bactrocera neohumeralis,* (9) *Bactrocera tryoni,* (10) *Ceratitis capitata,* (11) *Zeugodacus cucumis*. (A) current habitat suitability modelled using Maxent – values close to zero represent areas with low climatic suitability while values closer to one indicate higher climatic suitability; (B) areas considered "suitable" (i.e., with habitat suitability values above the 10th percentile at training presence sites, shown in red); (C, D, E) agreement about the suitability of habitat for the species across six climate scenarios for 2030, 2050 and 2070, respectively; (F) the location of Australian occurrence records of the species, which were used to calibrate models, based on specimens from natural history collections, literature and State Government trapping programs, and major commercial horticultural hosts, according to the Australian Horticulture Statistics Handbook (HSHB; www.horticulture.com.au).

(1) *Bactrocera aquilonis*



(2) *Bactrocera bryoniae*



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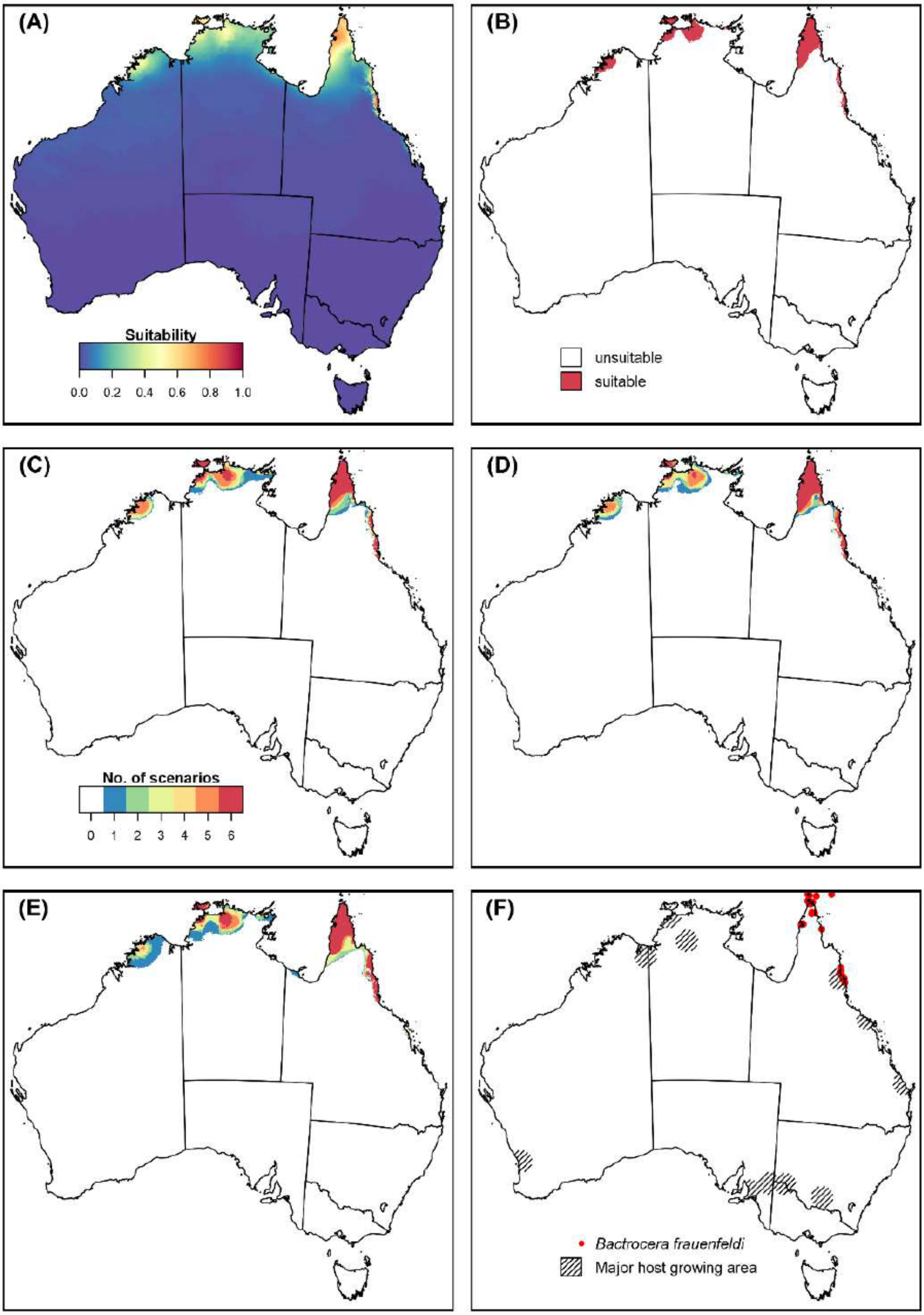
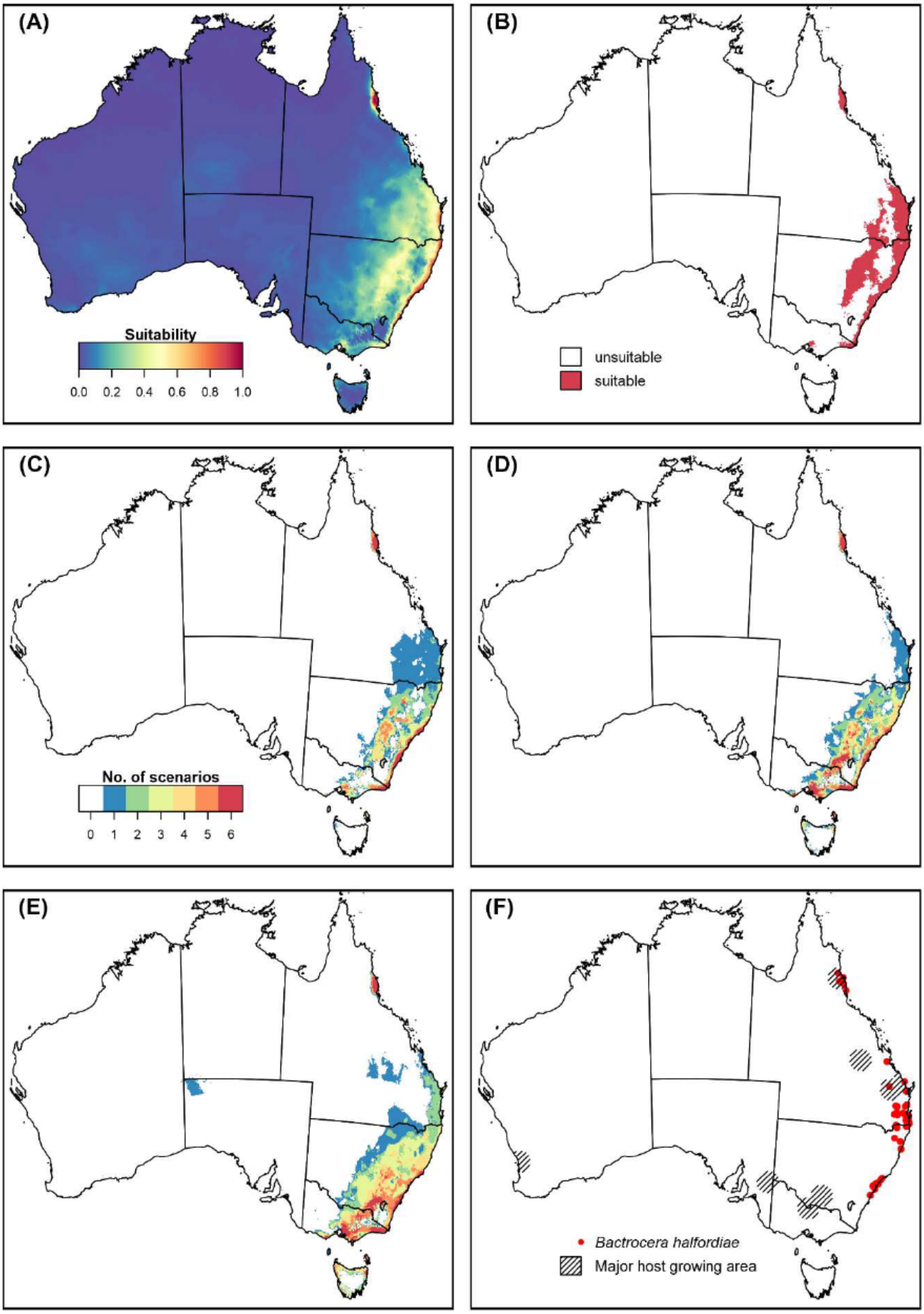


(4) *Bactrocera halfordiae*



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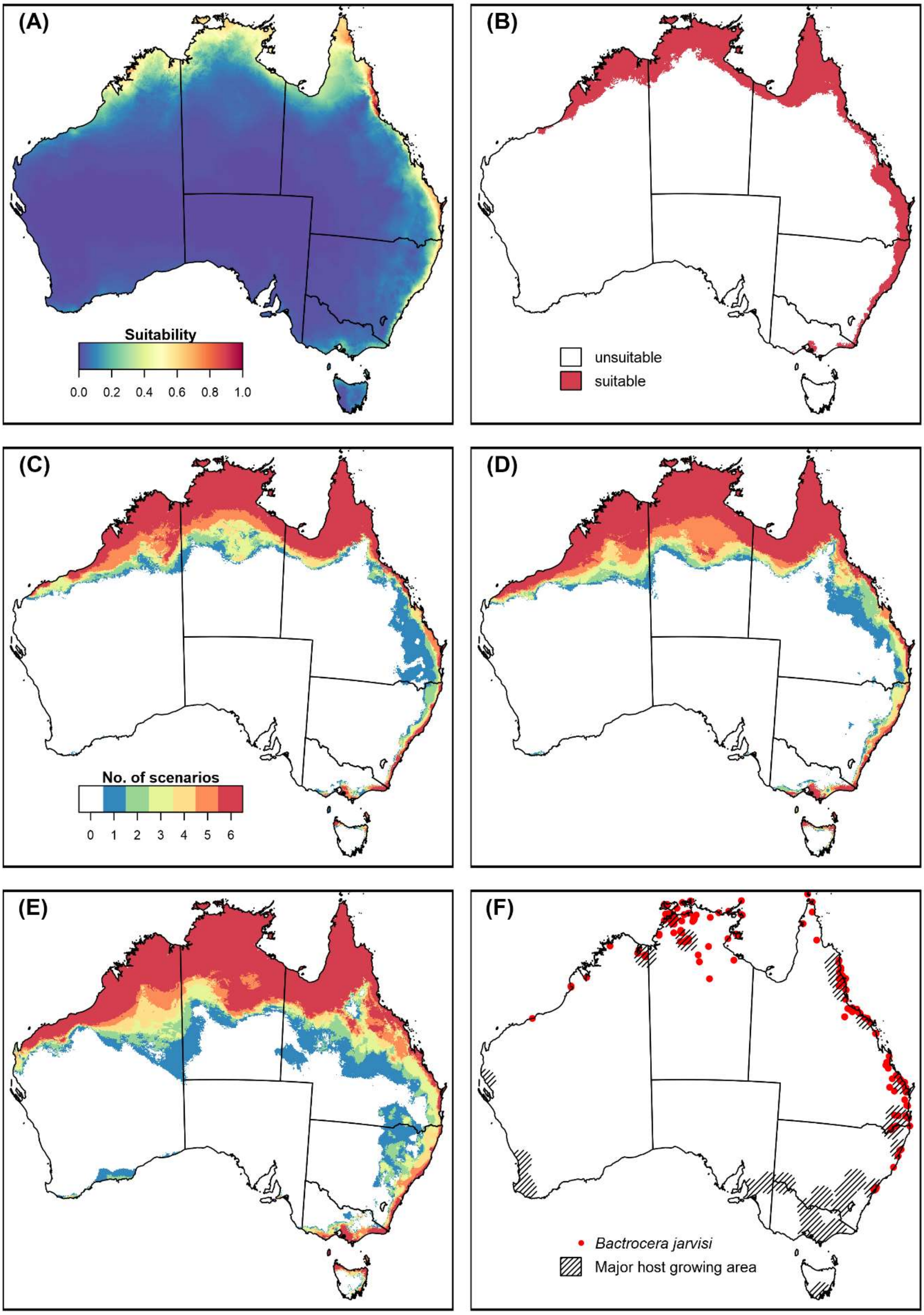

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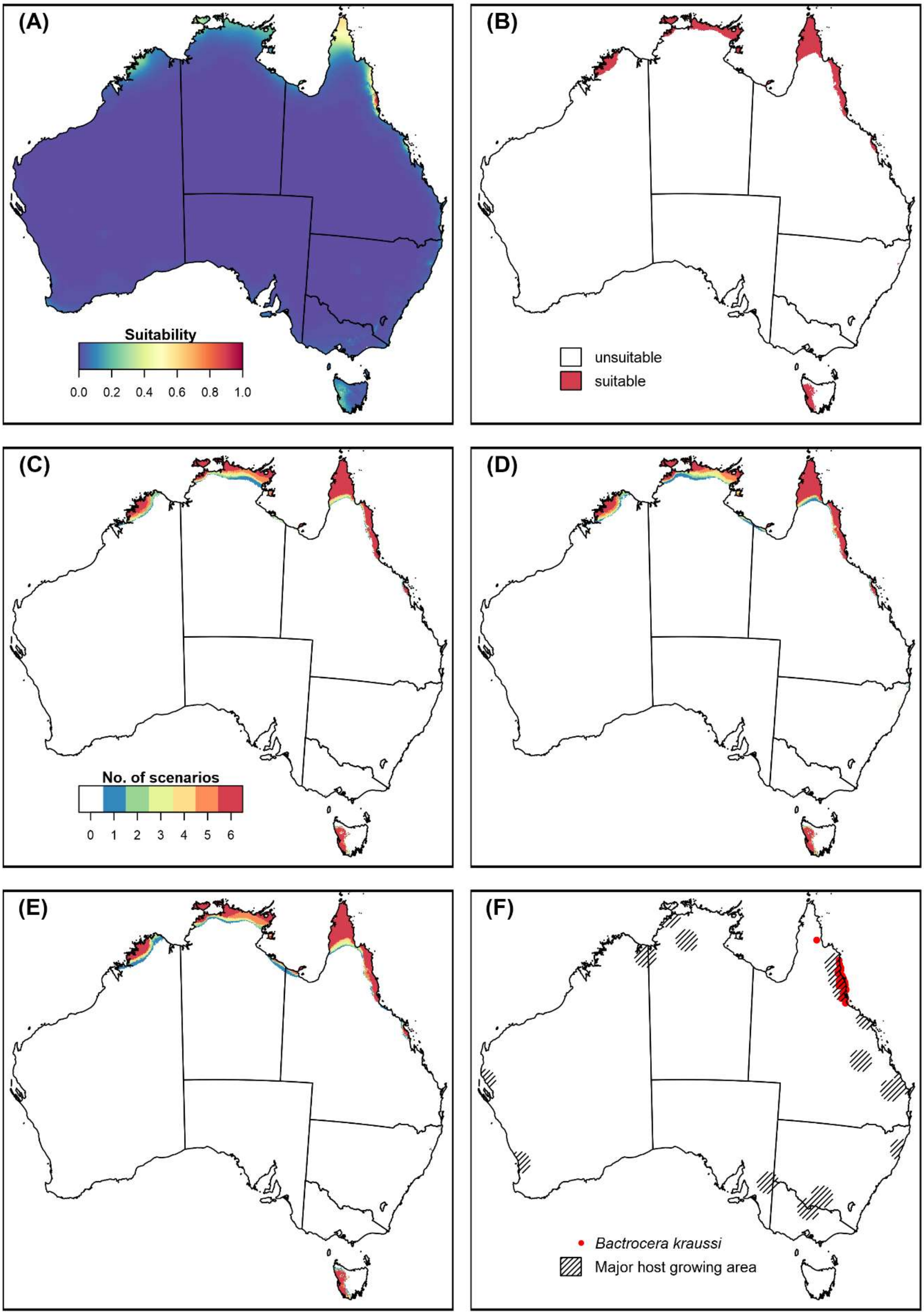
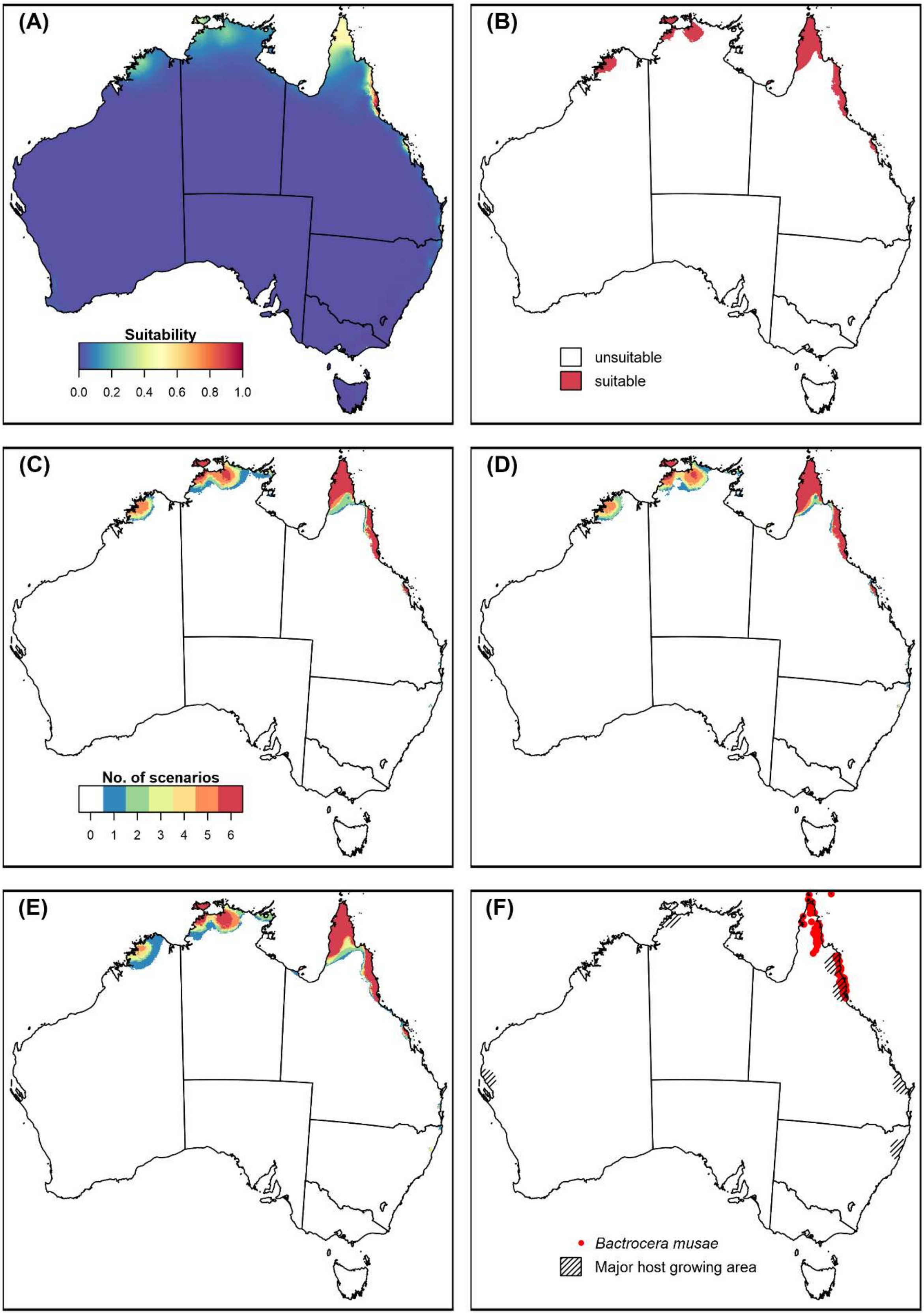
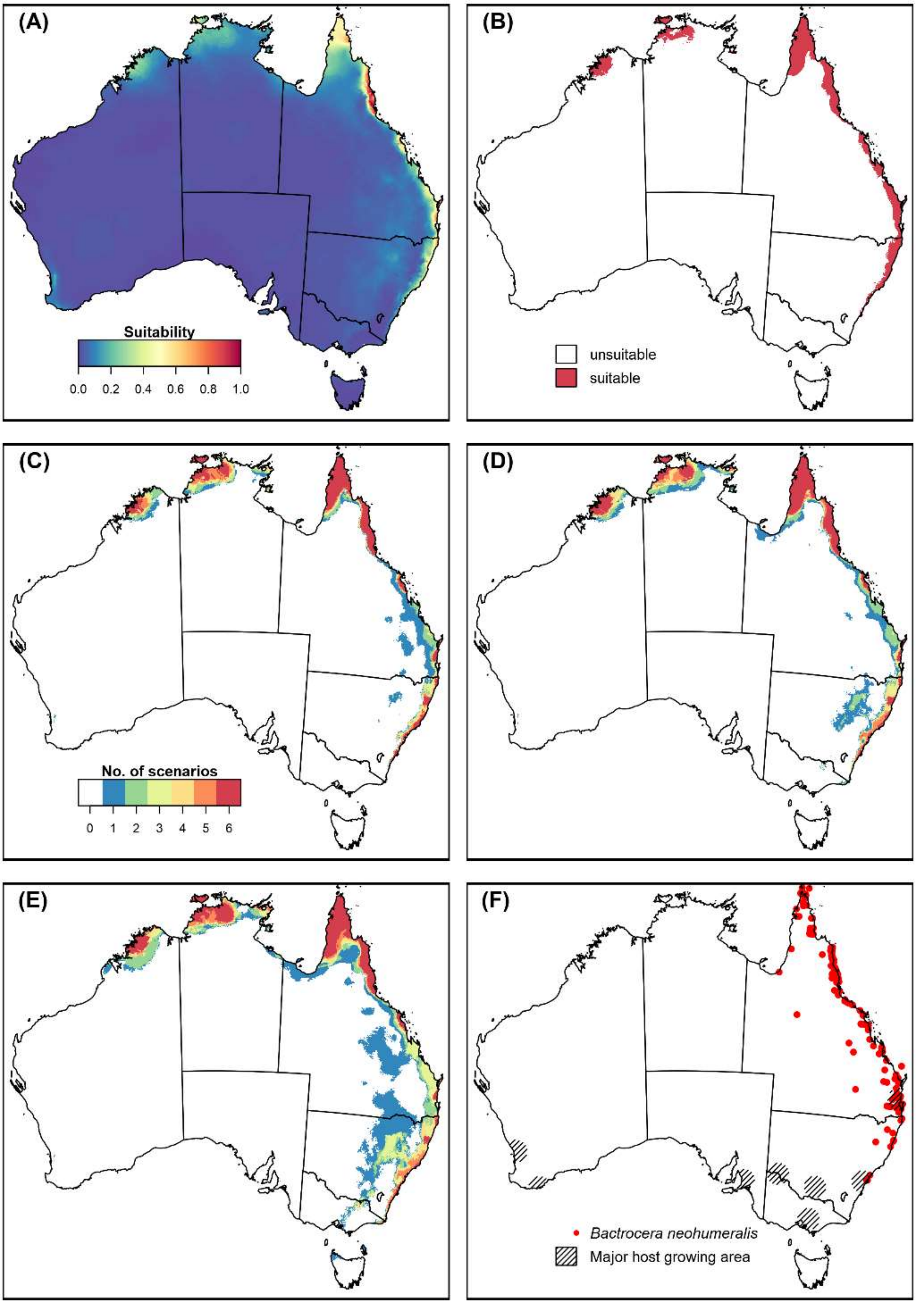


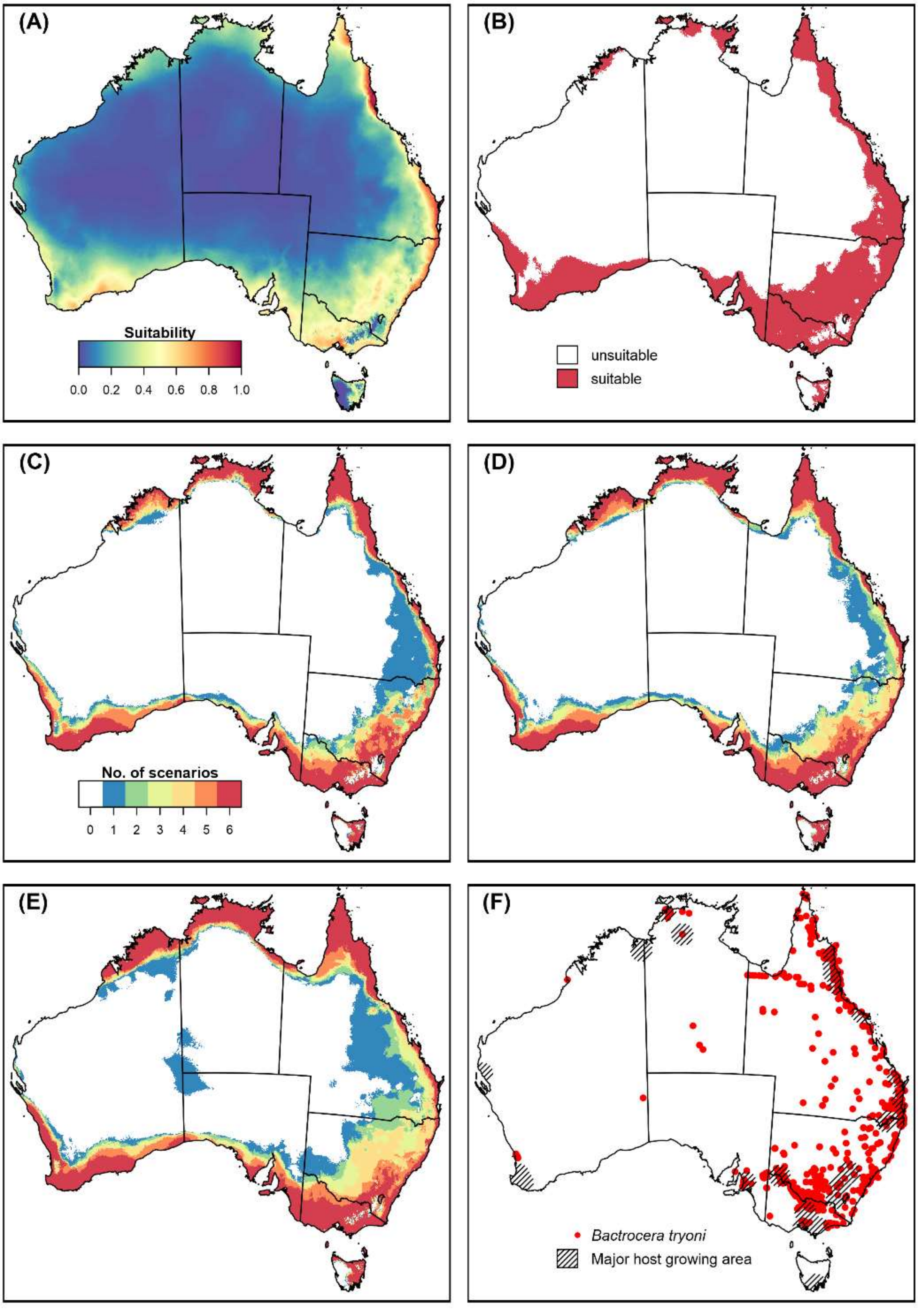
(7) *Bactrocera musae*



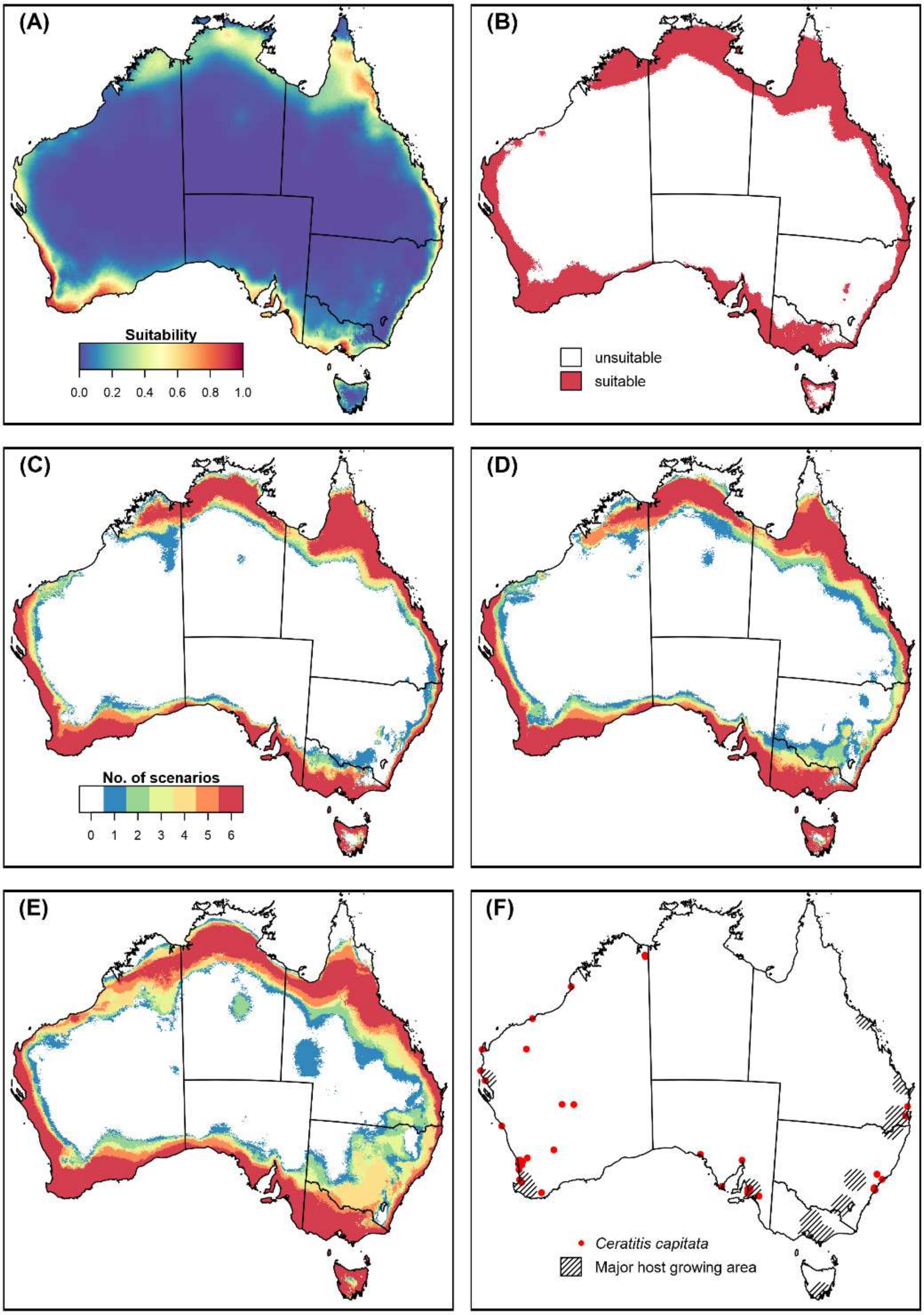
(8) *Bactrocera neohumeralis*



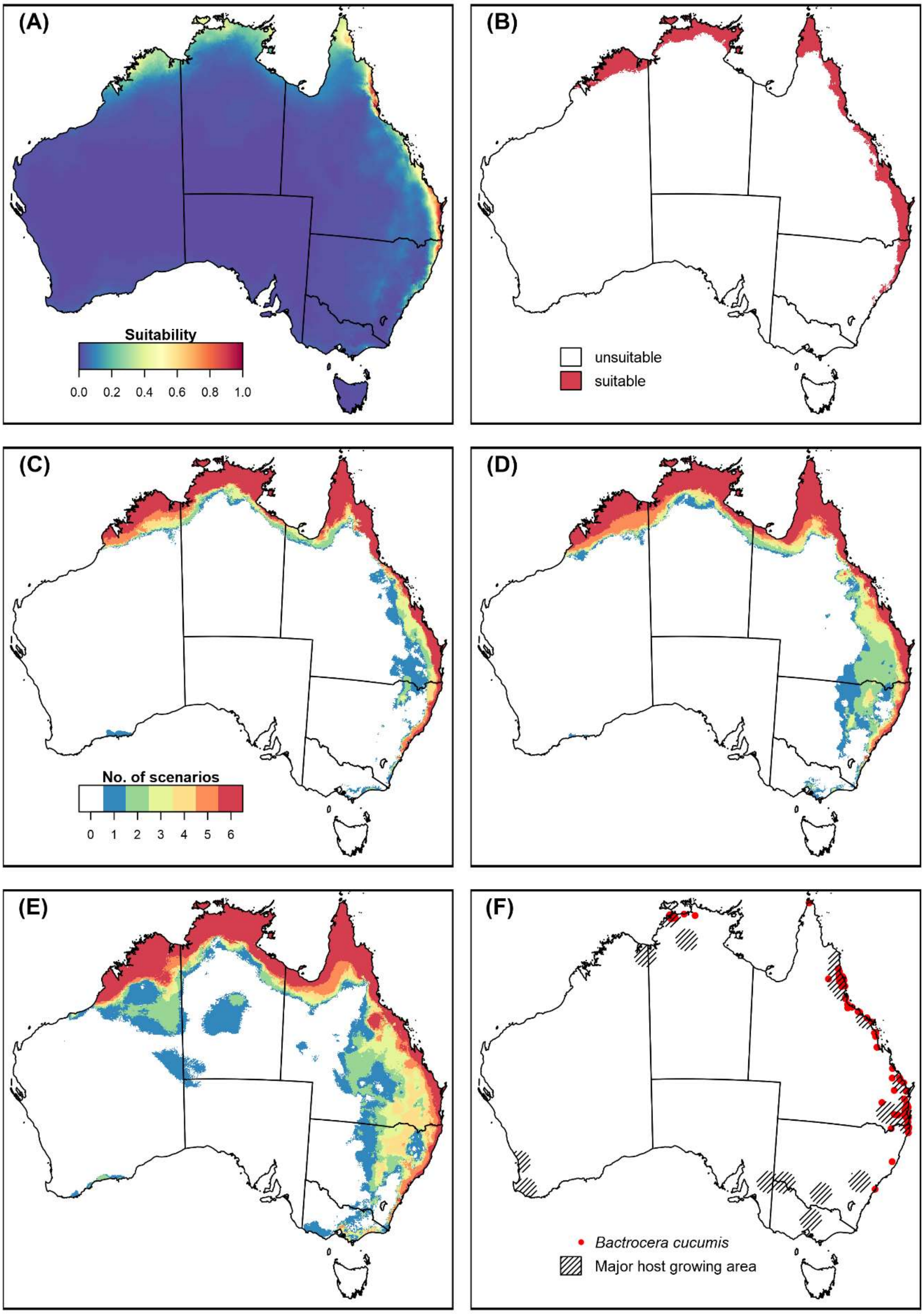
(9) *Bactrocera tryoni*



(10) *Ceratitis capitata*

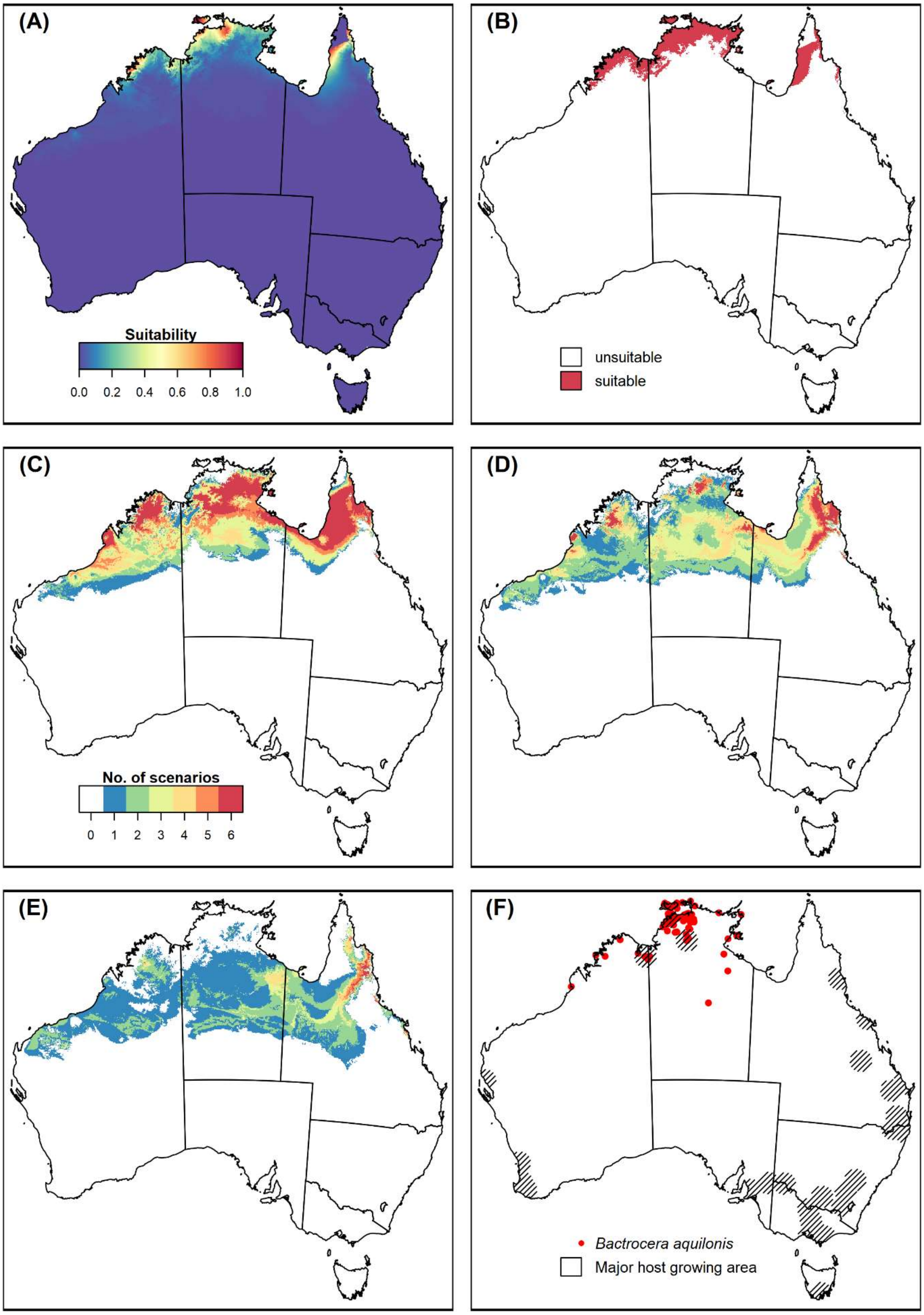


(11) *Zeugodacus cucumis*

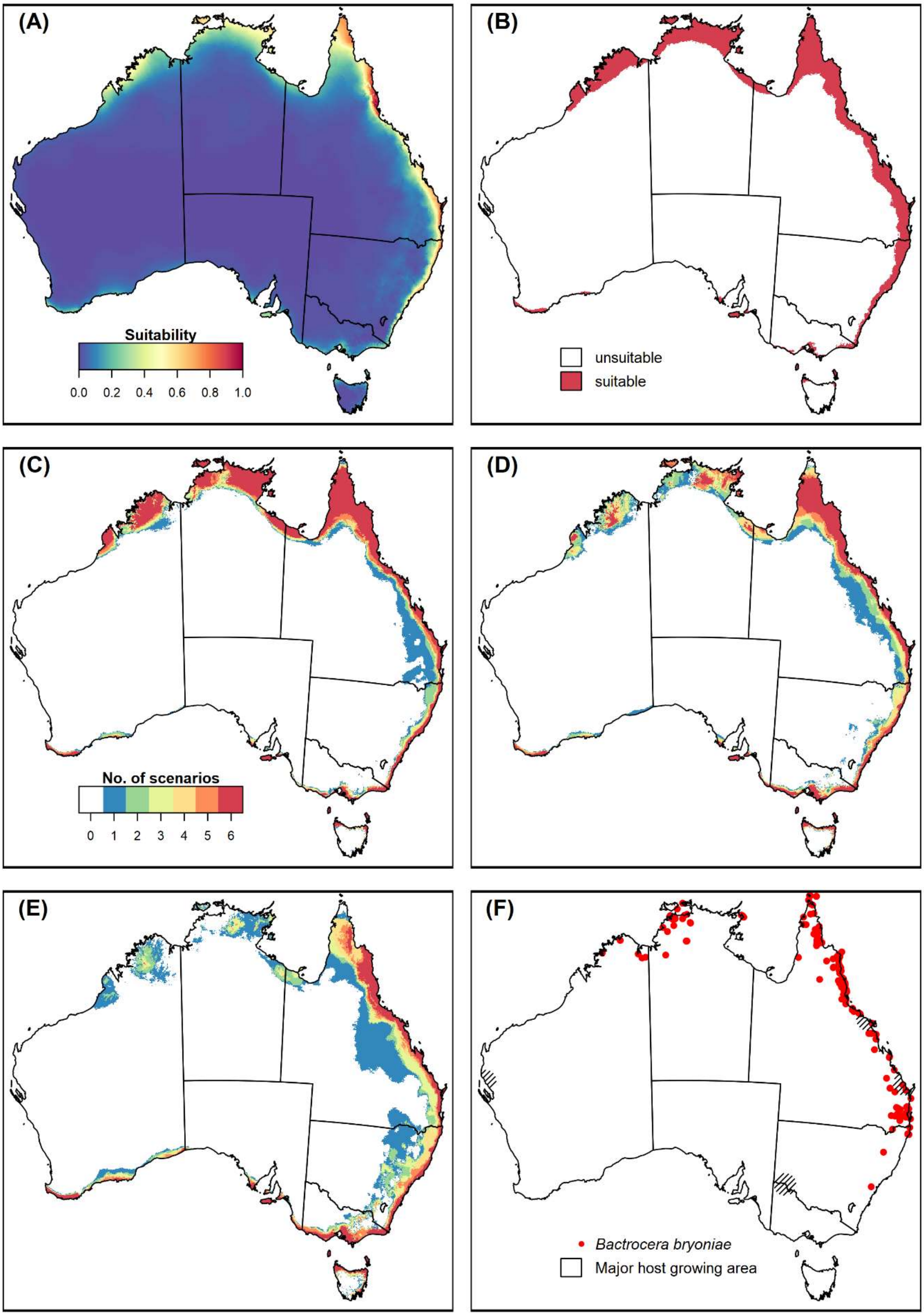


S12-22 Figs. Climatic habitat suitability for 11 tephritid fruit flies under various future climate scenarios, when novel environments are excluded. (12) *Bactrocera aquilonis,* (13) *Bactrocera bryoniae,* (14) *Bactrocera frauenfeldi,* (15) *Bactrocera halfordiae,* (16) *Bactrocera jarvisi,* (17) *Bactrocera kraussi,* (18) *Bactrocera musae,* (19) *Bactrocera neohumeralis,* (20) *Bactrocera tryoni,* (21) *Ceratitis capitata,* (22) *Zeugodacus cucumis*. (A) current habitat suitability modelled using Maxent – values close to zero represent areas with low climatic suitability while values closer to one indicate higher climatic suitability; (B) areas considered "suitable" (i.e., with habitat suitability values above the 10th percentile at training presence sites, shown in red); (C, D, E) agreement about the suitability of habitat for the species across six climate scenarios for 2030, 2050 and 2070, respectively; (F) the location of Australian occurrence records of the species, which were used to calibrate models, based on specimens from natural history collections, literature and State Government trapping programs, and major commercial horticultural hosts, according to the Australian Horticulture Statistics Handbook (HSHB; www.horticulture.com.au).

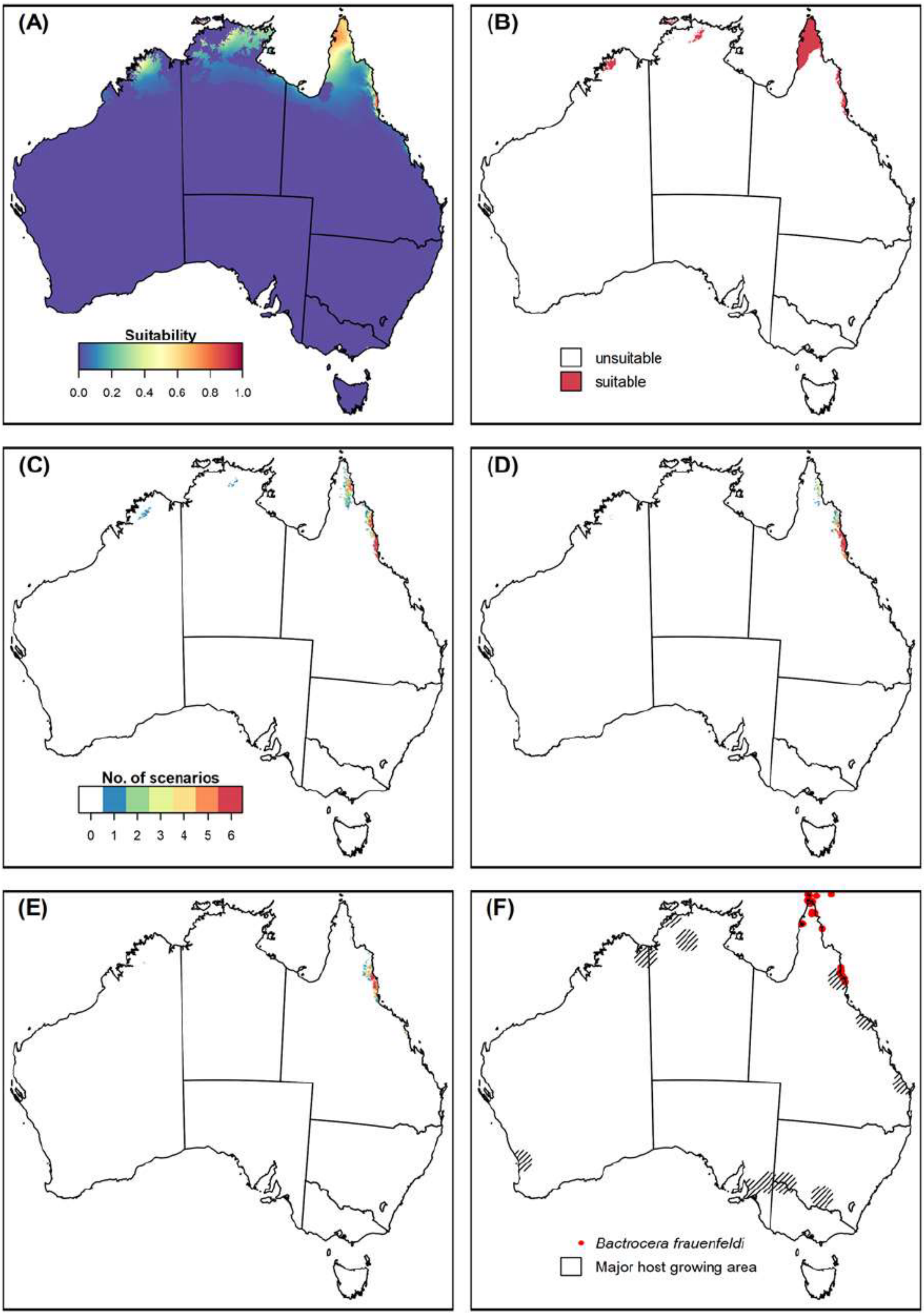
(12) *Bactrocera aquilonis*



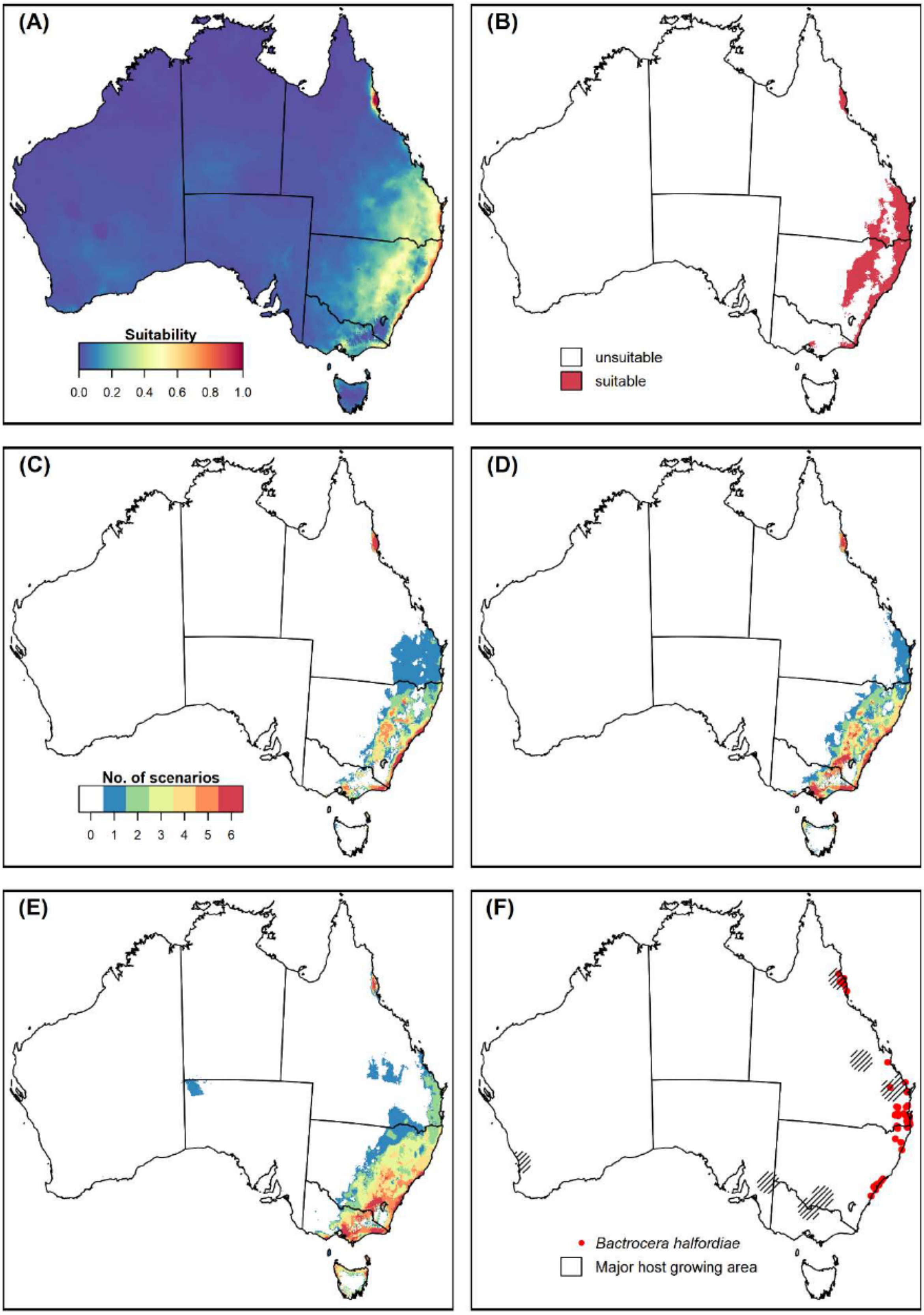
(13) *Bactrocera bryoniae*



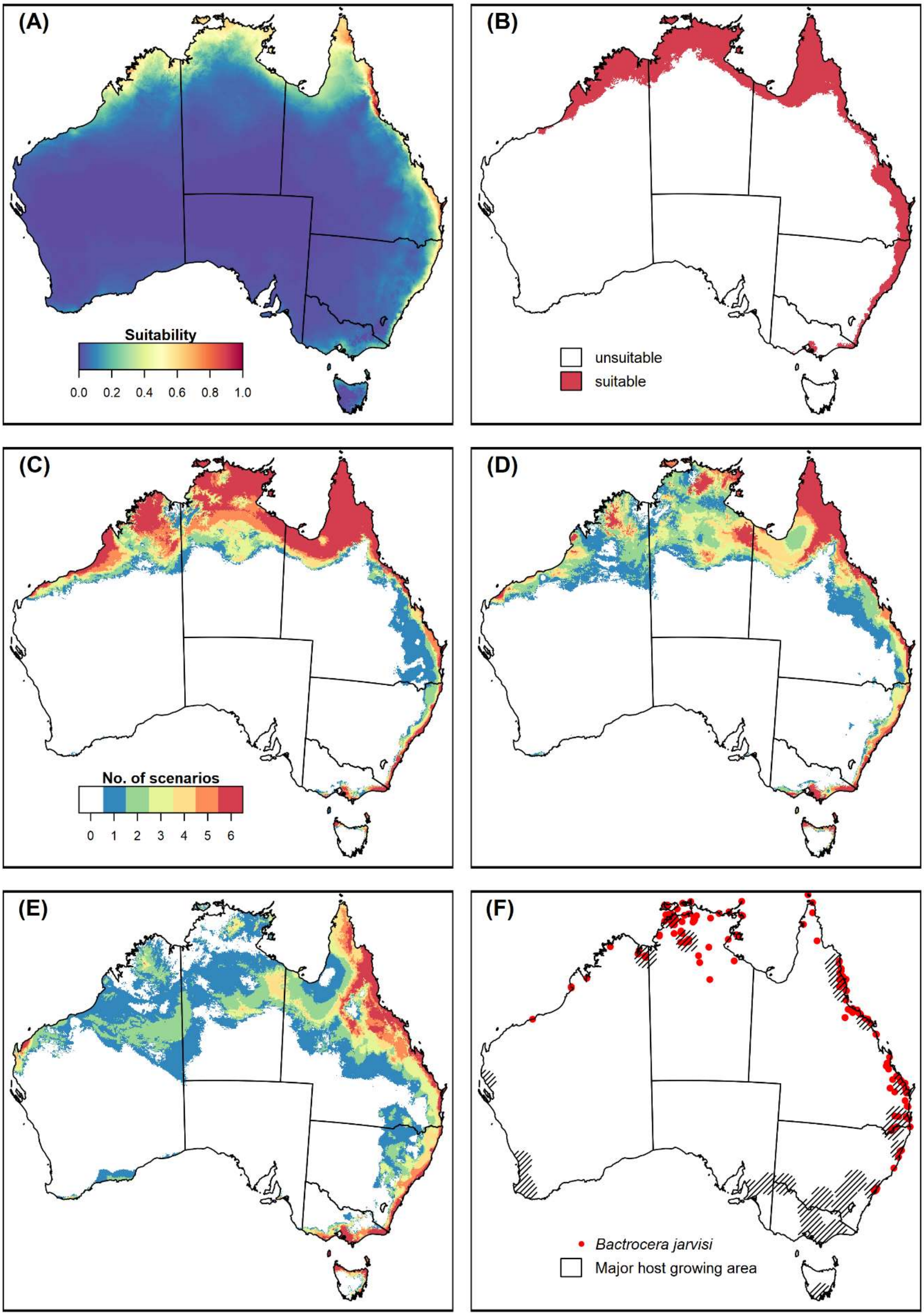
(14) *Bactrocera frauenfeldi*



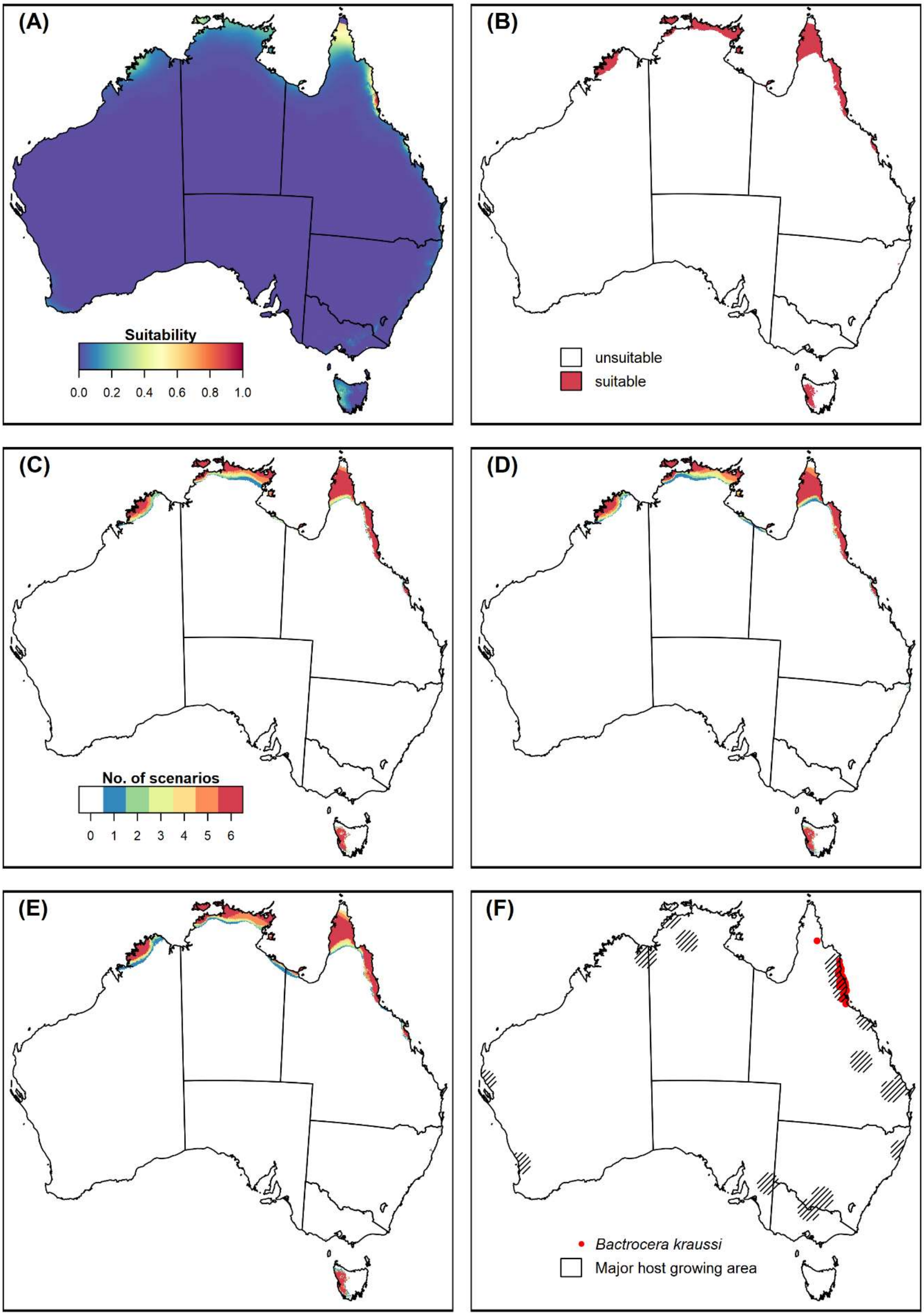
(15) *Bactrocera halfordiae*



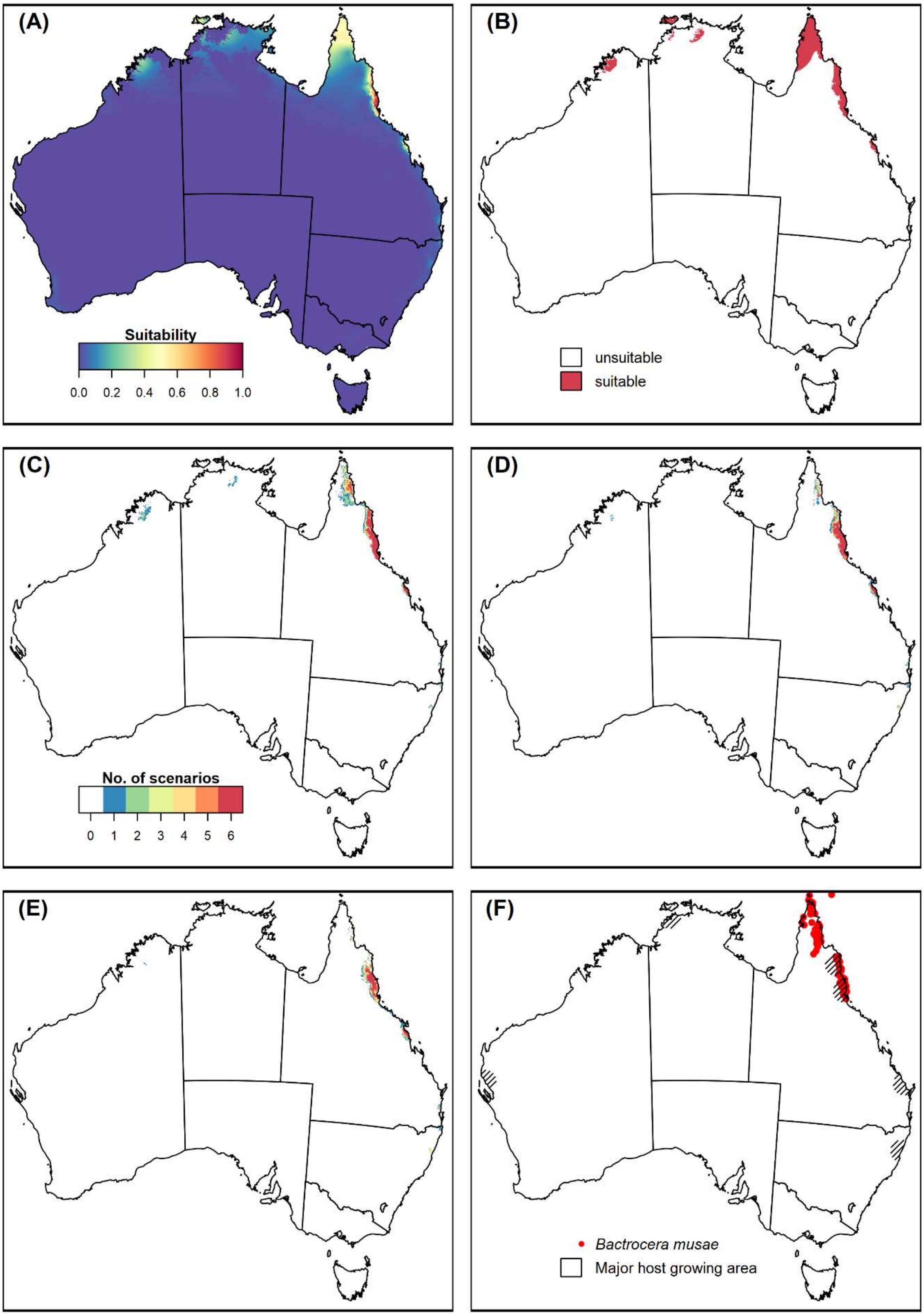
(16) *Bactrocera jarvisi*



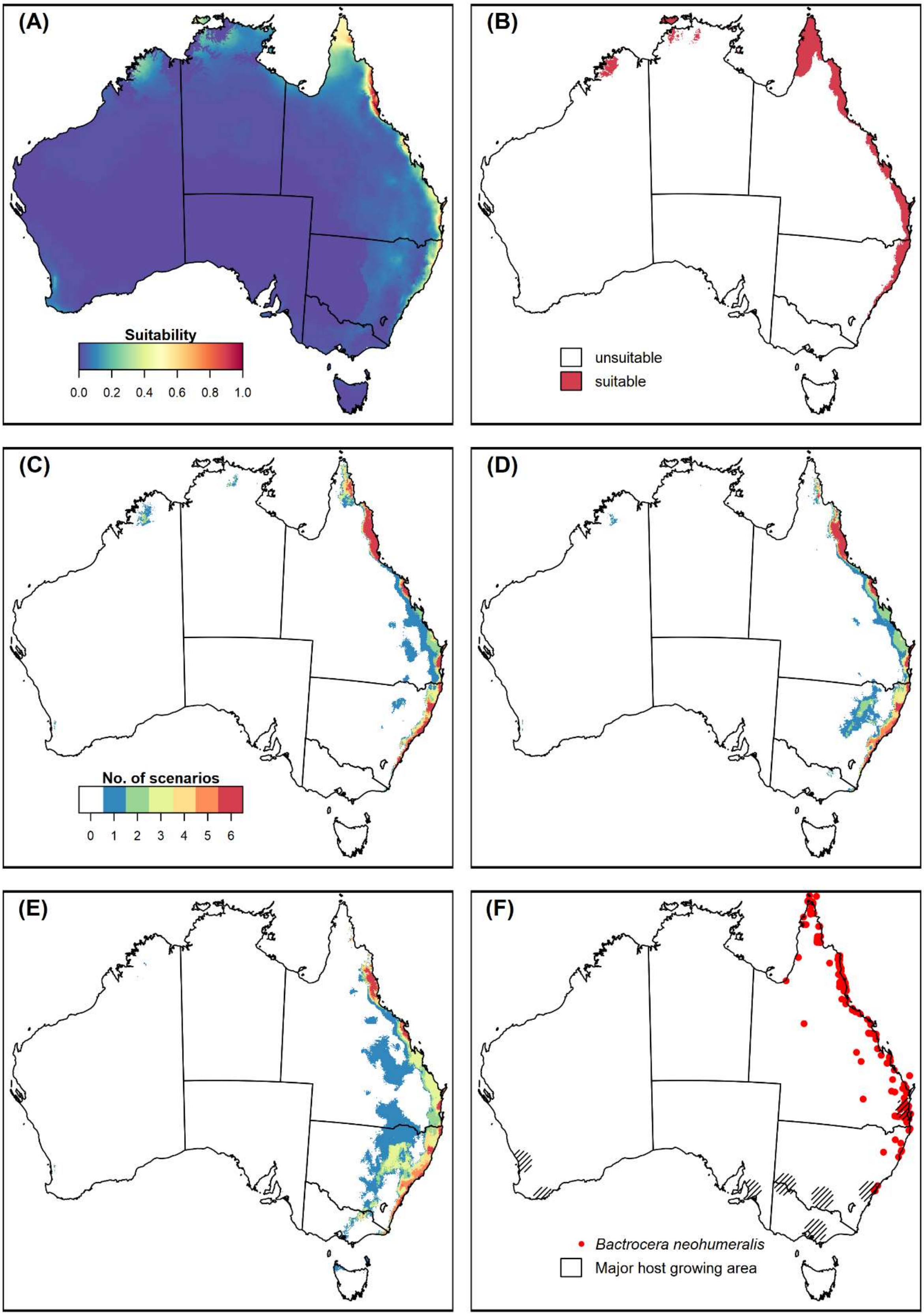
(17) *Bactrocera kraussi*



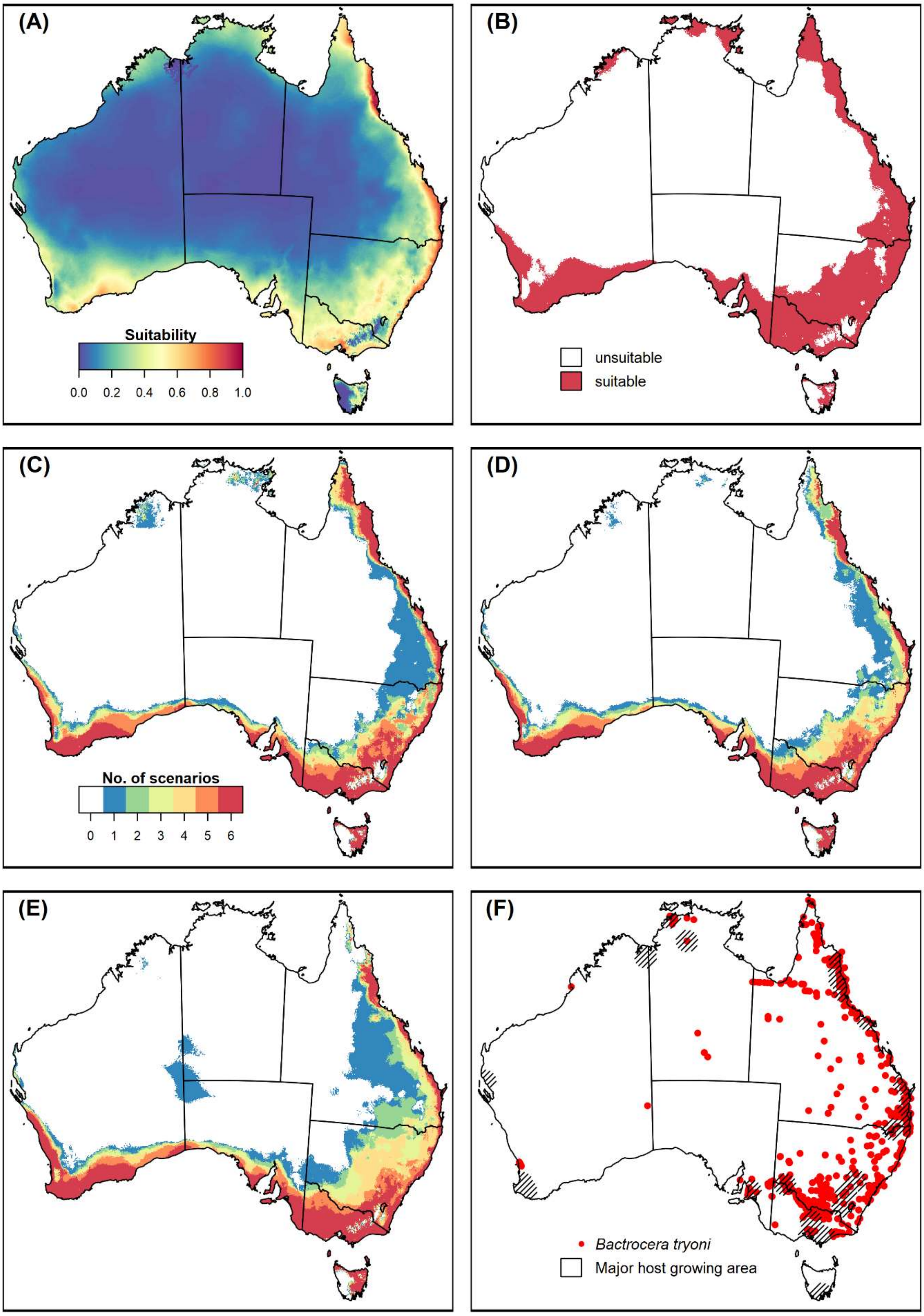
(18) *Bactrocera musae*



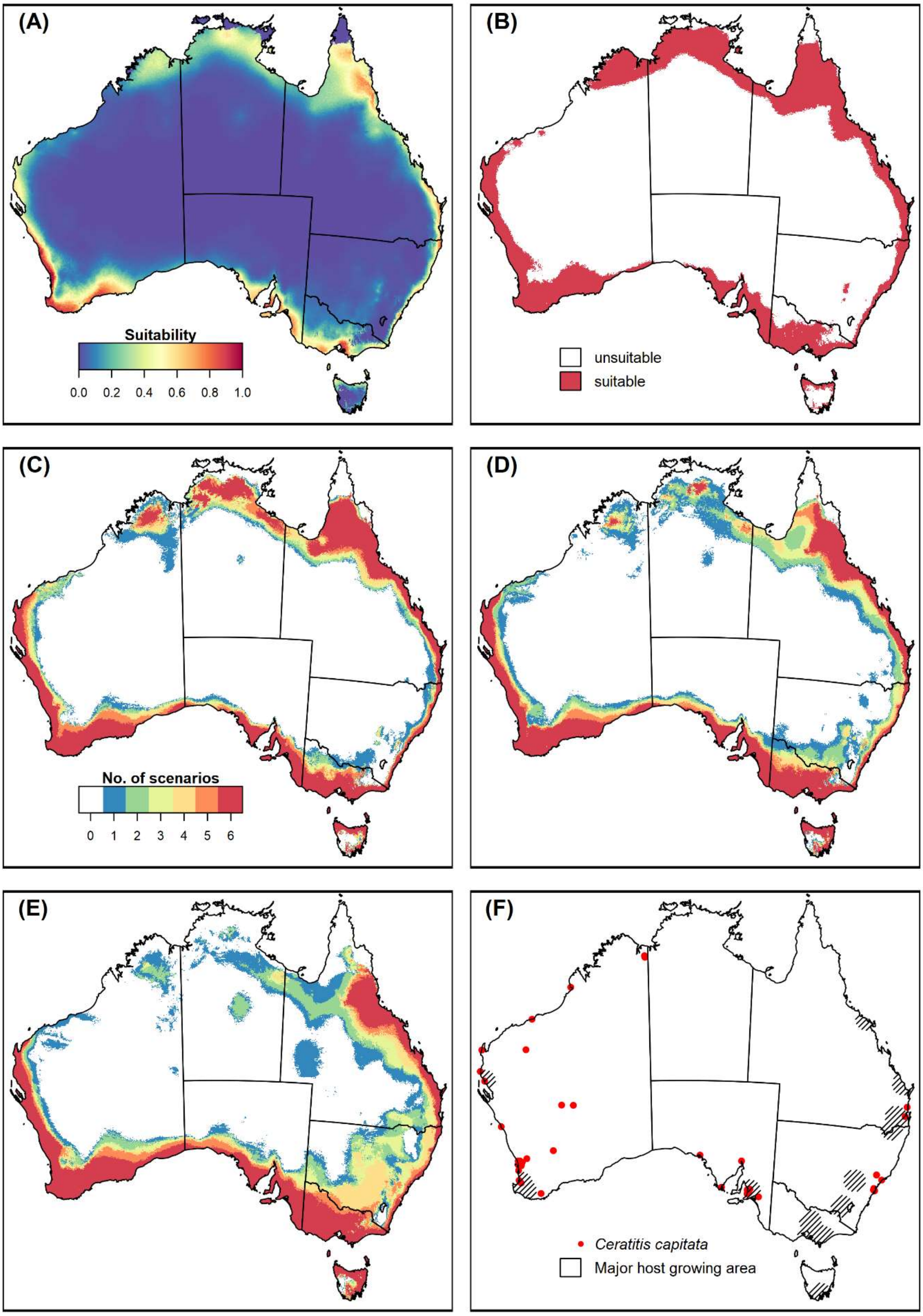
(19) *Bactrocera neohumeralis*



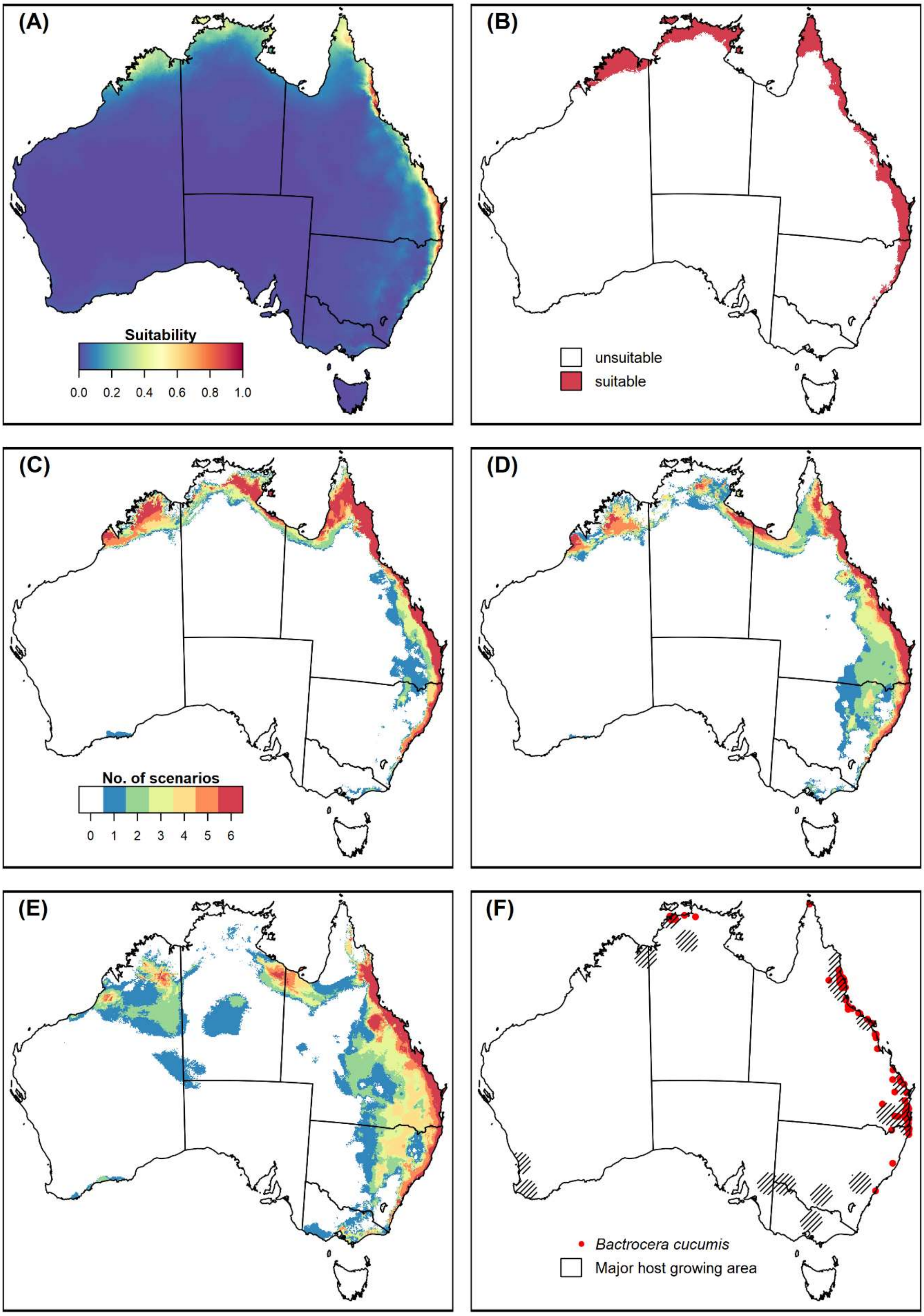
(20) *Bactrocera tryoni*



(21) *Ceratitis capitata*

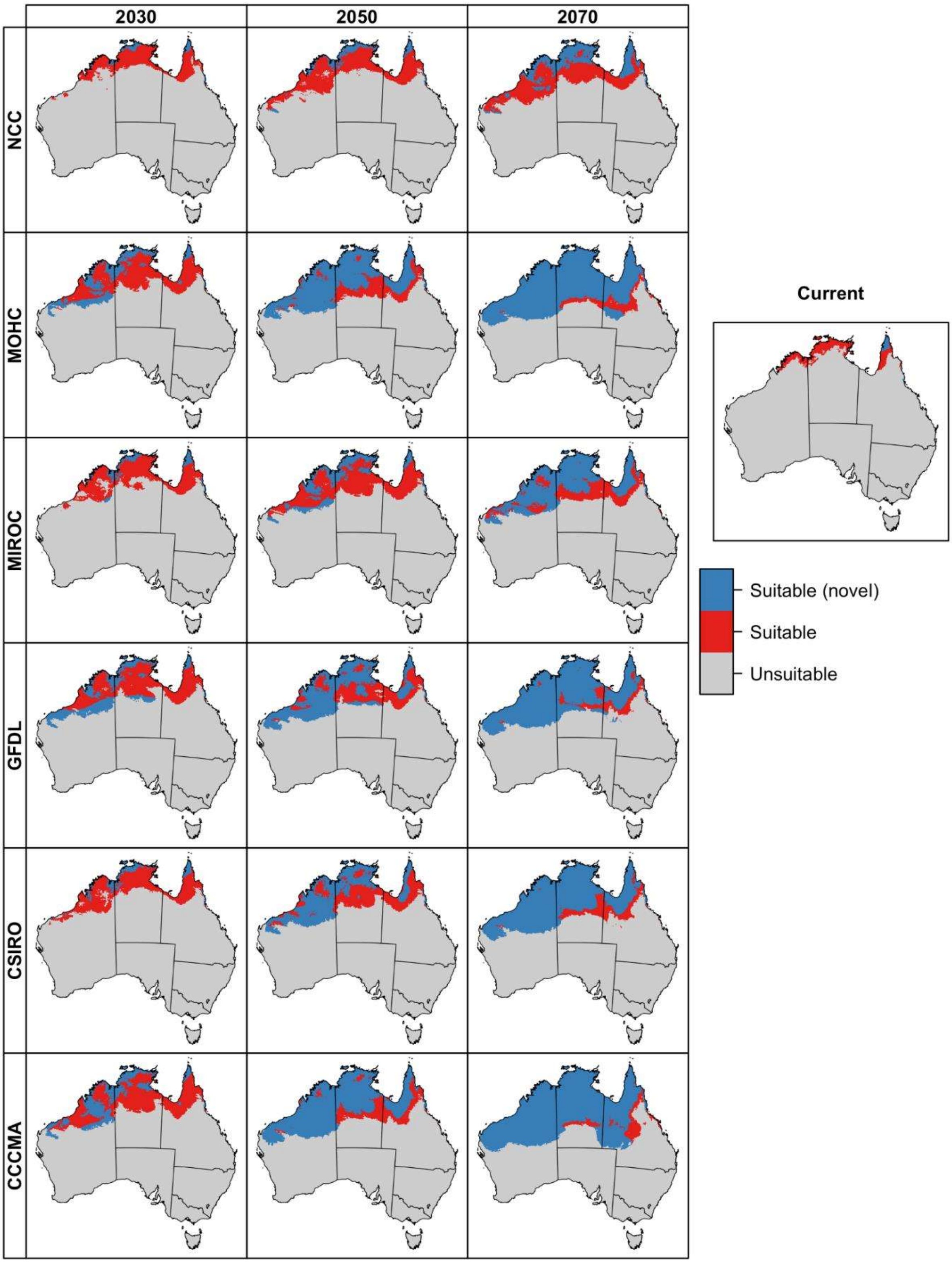


(22) *Zeugodacus cucumis*

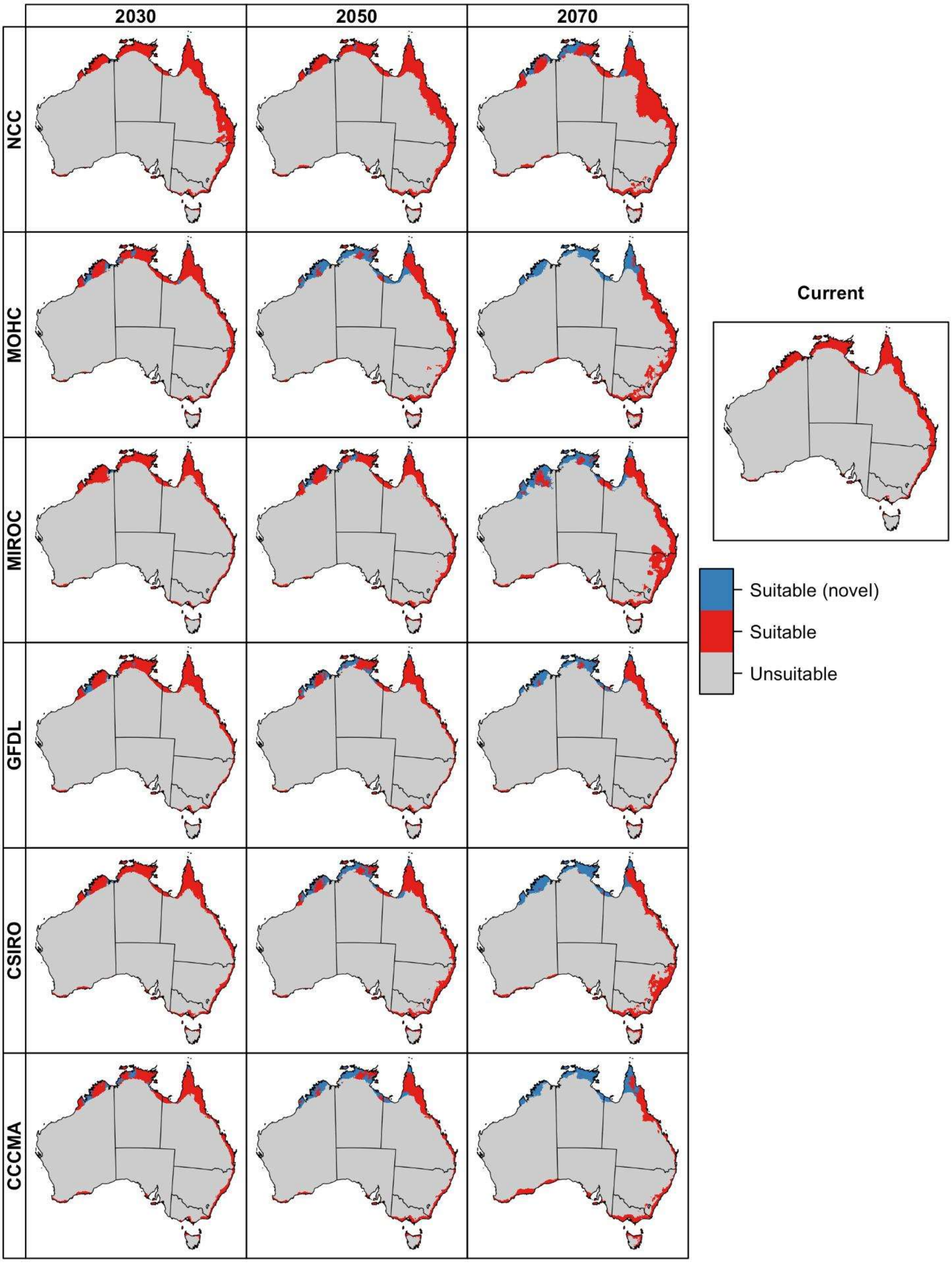


S23-33 Figs. Projected changes of suitable habitat for all 11 fruit fly species, under six future climate scenarios, relative to the current period. (23) *Bactrocera aquilonis,* (24) *Bactrocera bryoniae,* (25) *Bactrocera frauenfeldi,* (26) *Bactrocera halfordiae,* (27) *Bactrocera jarvisi,* (28) *Bactrocera kraussi,* (29) *Bactrocera musae,* (30) *Bactrocera neohumeralis,* (31) *Bactrocera tryoni,* (32) *Ceratitis capitata,* (33) *Zeugodacus cucumis.* Colours indicate projected changes of suitable habitat of species under future climate scenarios, where blue colour indicates suitability with novel environments, red colour indicates suitability without novel environments and gray colour indicates unsuitability.

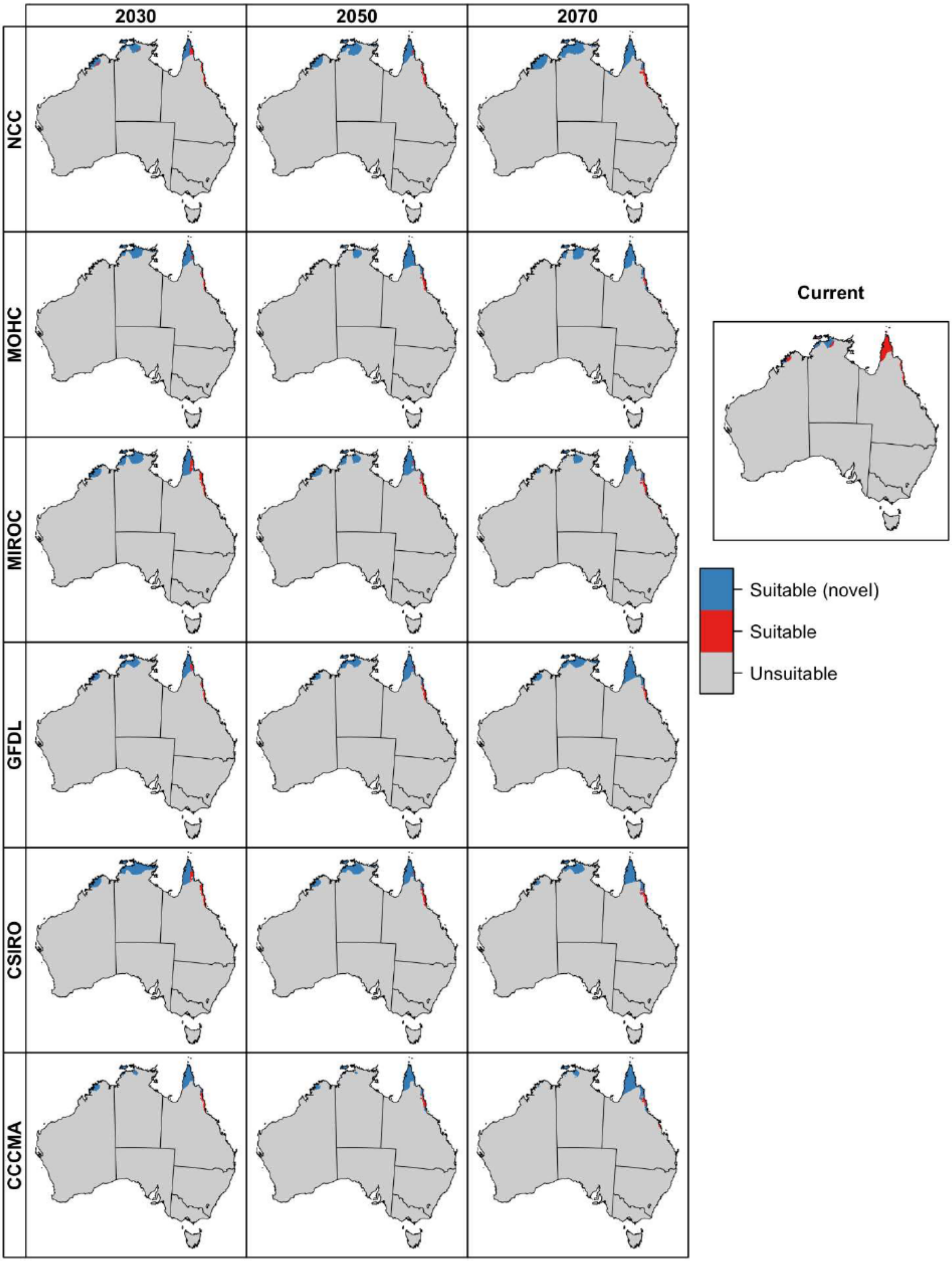
(23) *Bactrocera aquilonis*



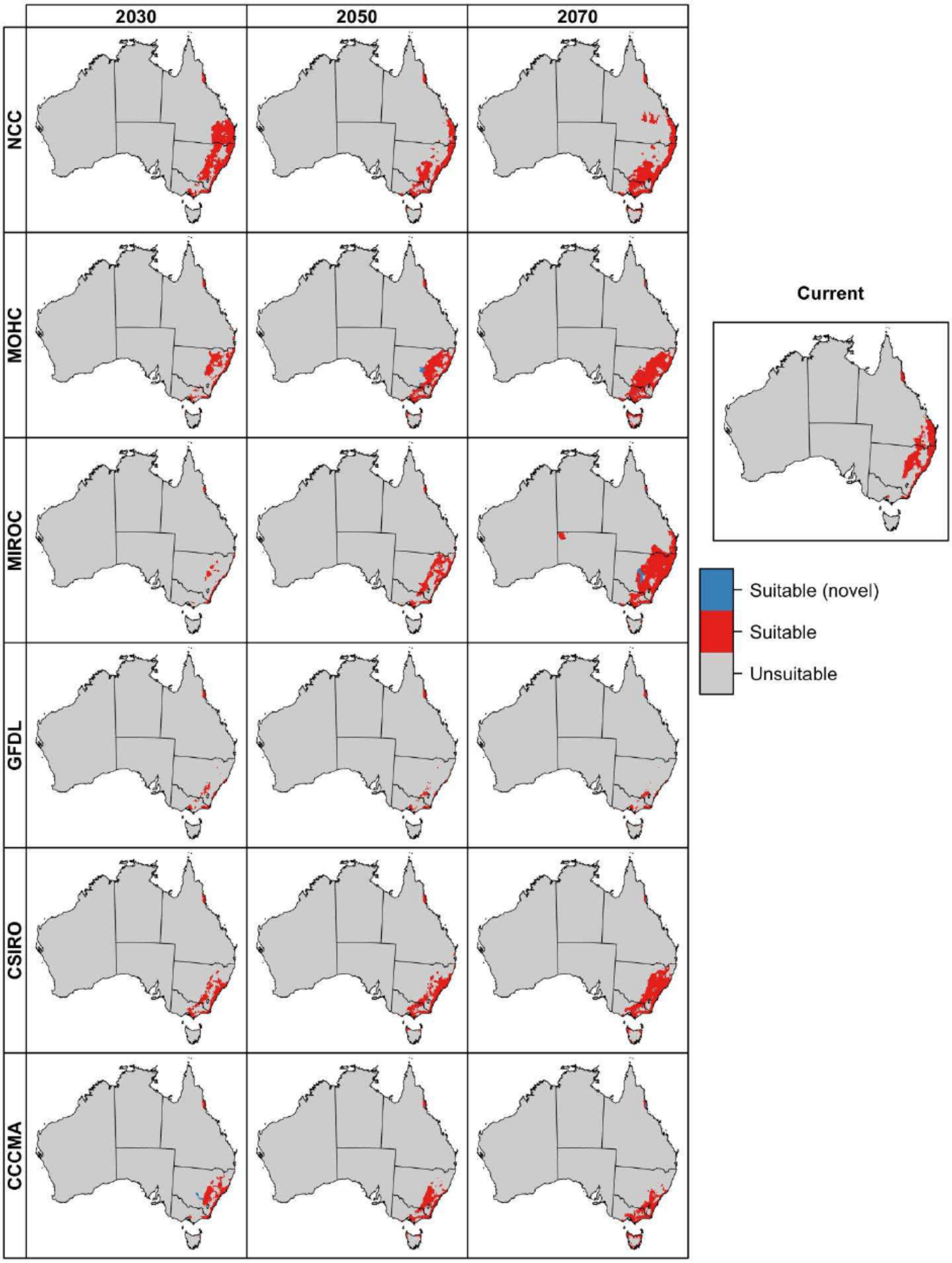
(24) *Bactrocera bryoniae*



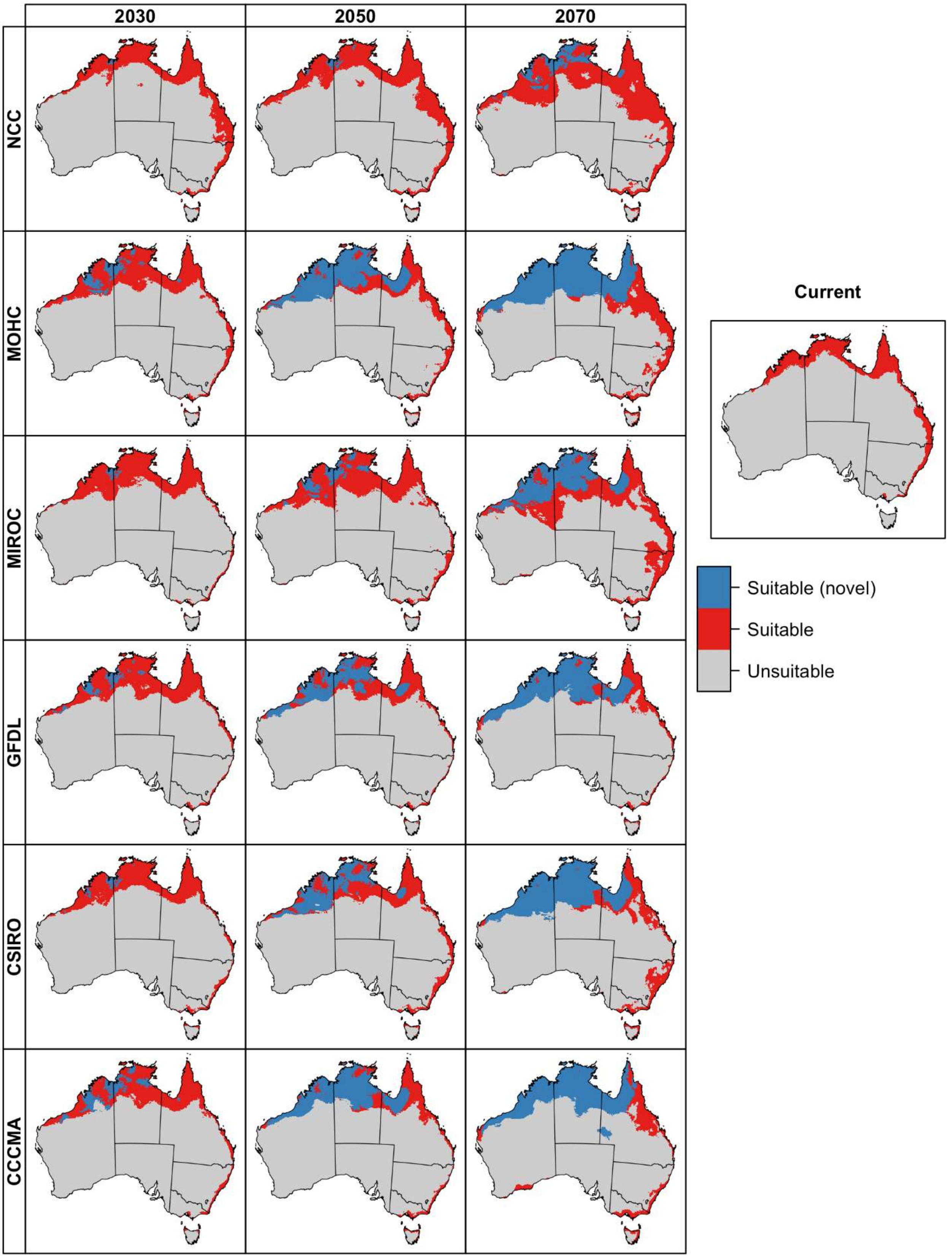
(25) *Bactrocera frauenfeldi*



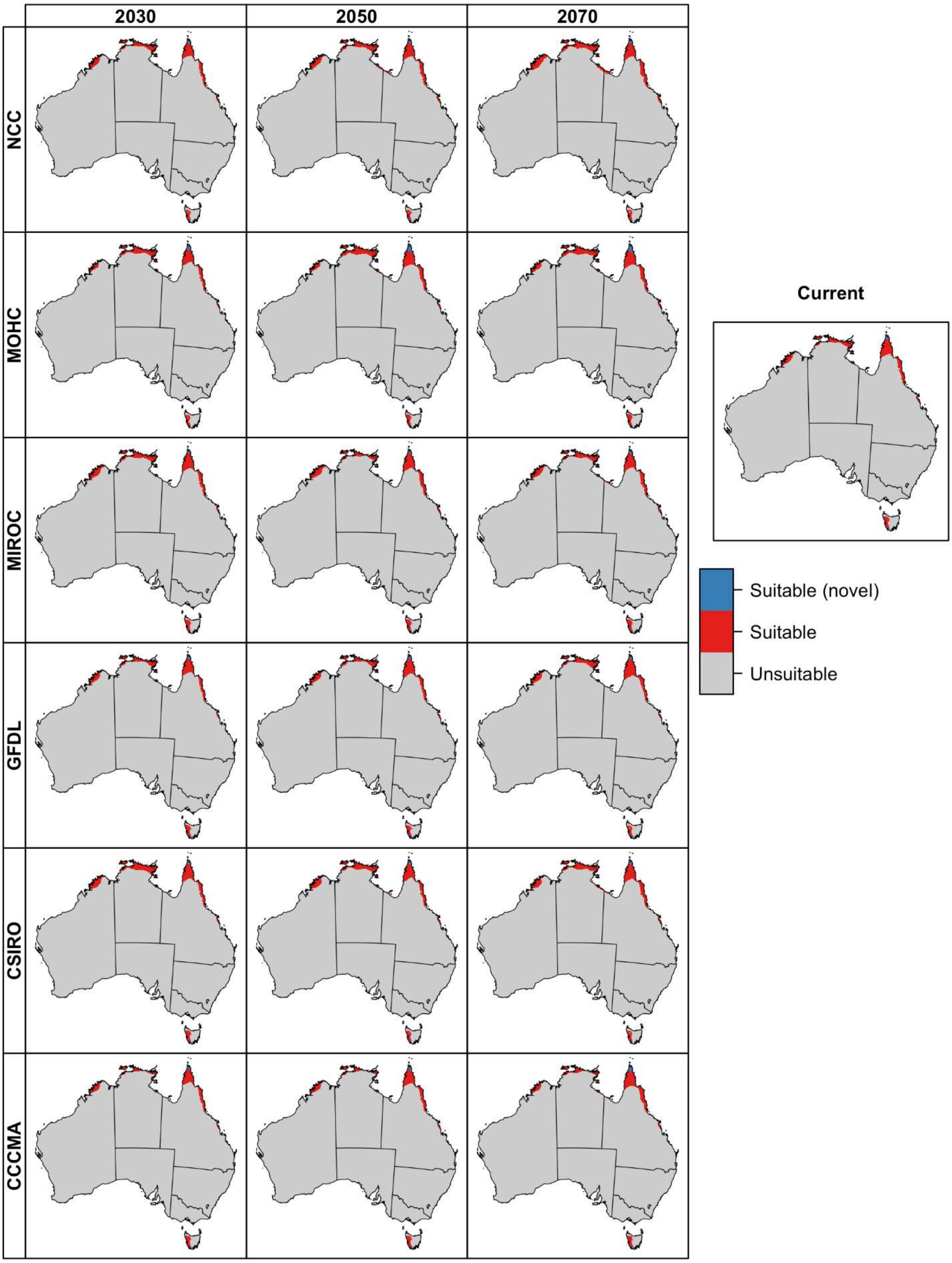
(26) *Bactrocera halfordiae*



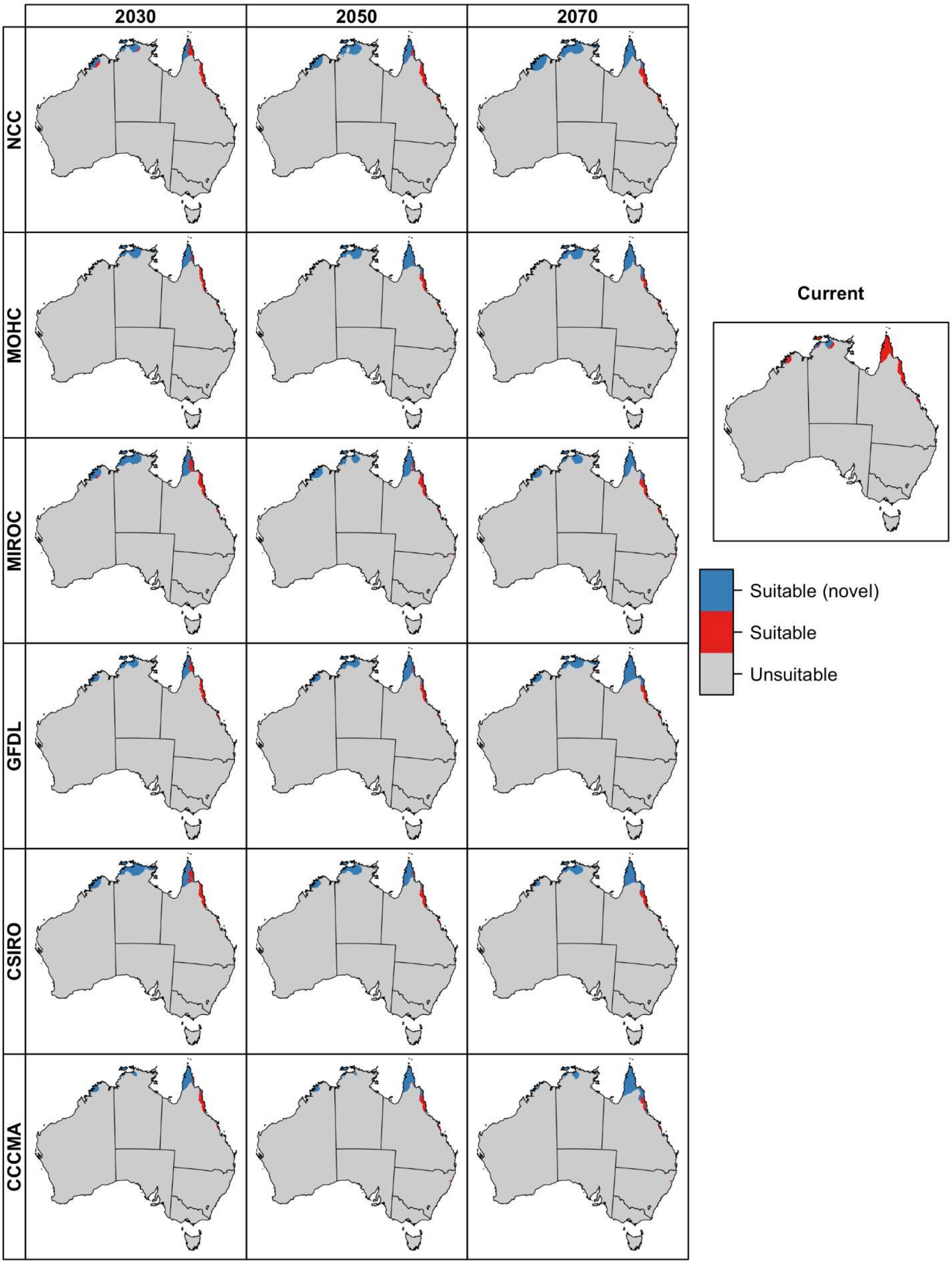
(27) *Bactrocera jarvisi*



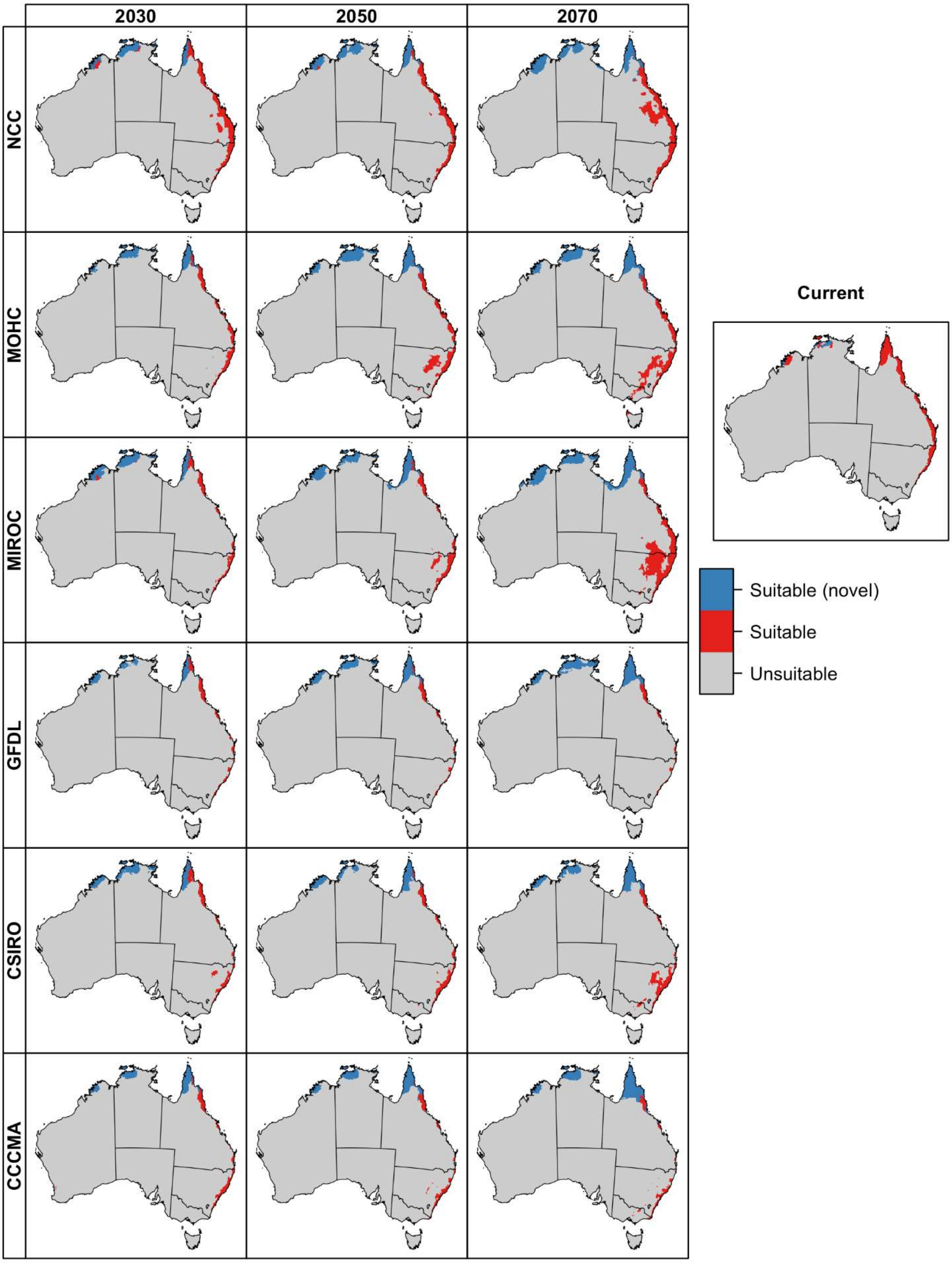
(28) *Bactrocera kraussi*



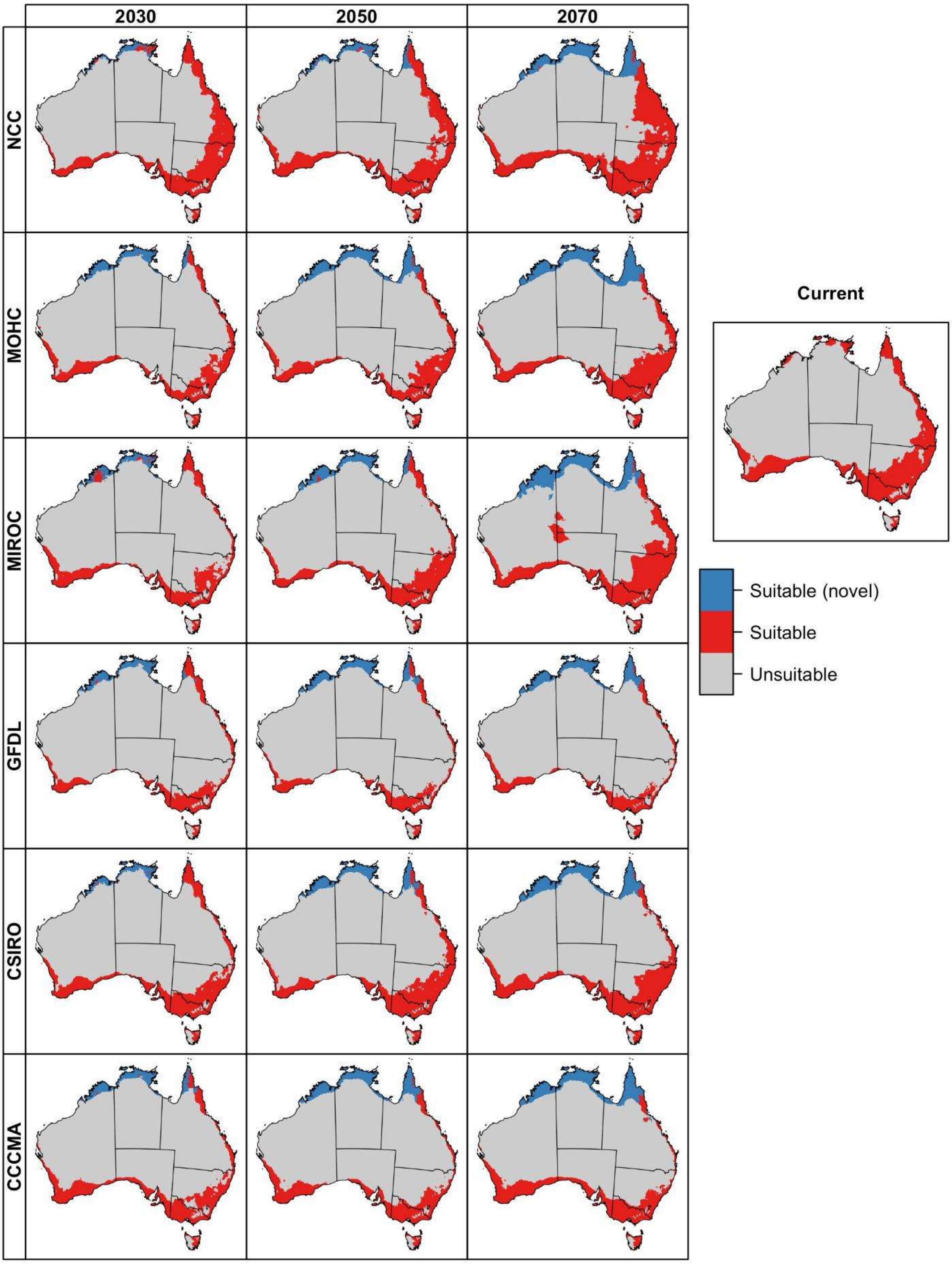
(29) *Bactrocera musae*



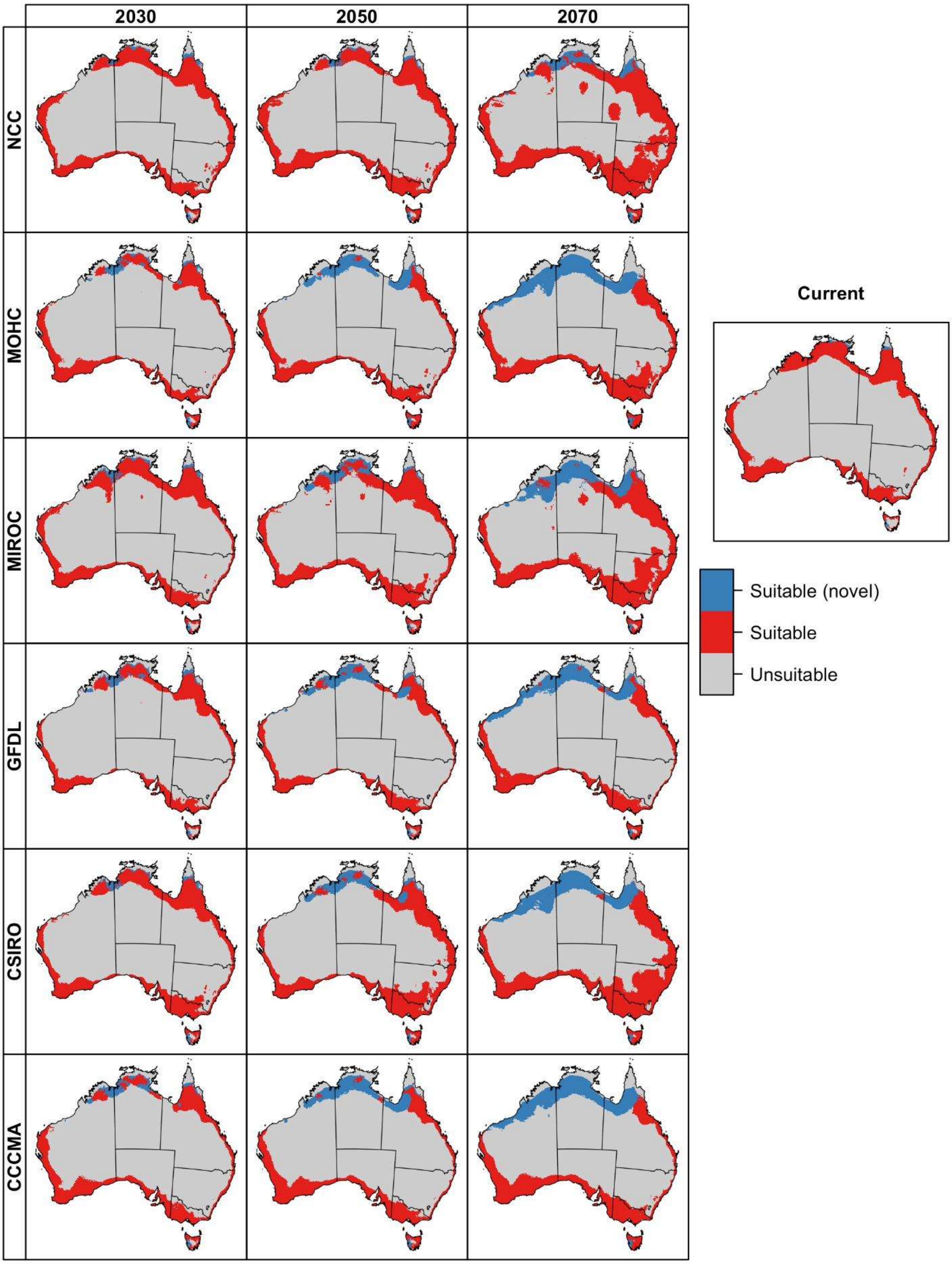
(30) *Bactrocera neohumeralis*



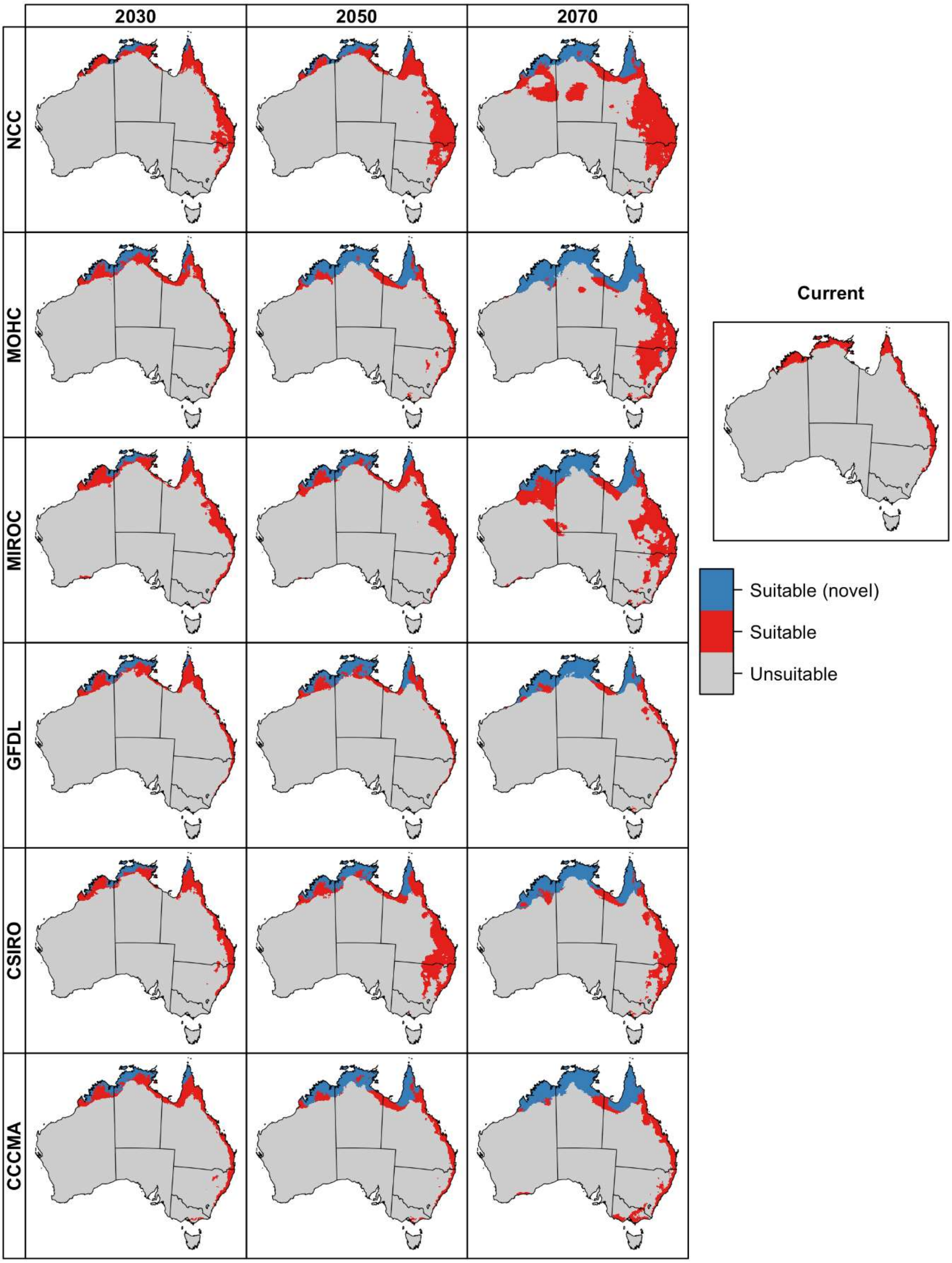
(31) *Bactrocera tryoni*



(32) *Ceratitis capitata*



(33) *Zeugodacus cucumis*



S1 Table. Model performance and bioclimatic variables used to investigate the suitability of habitat for tephritid fruit fly species. AUC value indicates the area under the receiver operating characteristic curve (average of 5 cross-validated replicates), which was used to evaluate model performance; SD (standard deviation); and HPI (highest permutation importance, %) of bioclimatic variables contributing to the model where BIO01: annual mean temperature, BIO02: mean diurnal range; BIO03: isothermality; BIO06: minimum temperature of the coldest month; BIO07: temperature annual range; BIO11: mean temperature of the coldest quarter; BIO13: precipitation of the wettest month; BIO14: precipitation of the driest month; BIO16: precipitation of the wettest quarter; BIO17: precipitation of the driest quarter and BIO19: precipitation of the coldest quarter.

Species	**AUC**	**SD**	**HPI (Highest Permutation Importance, %)**
Bactrocera aquilonis	0.896	0.02	BIO16: 68.9, BIO01: 28.9, BIO11: 2.5
Bactrocera bryoniae	0.853	0.03	BIO01: 24.3, BIO06: 6.1, BIO07: 42.2, BIO14: 27.4
Bactrocera frauenfeldi	0.815	0.05	BIO01: 21.7, BIO13: 3.2, BIO16: 75.4
Bactrocera halfordiae	0.846	0.03	BIO01: 32.3, BIO03: 0.9, BIO14: 66.8
Bactrocera jarvisi	0.817	0.04	BIO01: 37.9, BIO07: 24.7, BIO14: 37.2
Bactrocera kraussi	0.904	0.05	BIO02: 24.7, BIO13: 0.1, BIO16: 75.2
Bactrocera musae	0.861	0.02	BIO01: 2.5, BIO13: 4.4, BIO14: 14.4, BIO16:78.7
Bactrocera neohumeralis	0.907	0.02	BIO01: 21.9, BIO03: 1.3, BIO13: 47.4, BIO14: 29.3
Bactrocera tryoni	0.841	0.01	BIO01: 33.1, BIO06:32.4, BIO07: 3.93, BIO14: 26.7, BIO19: 3.9
Ceratitis capitata	0.885	0.02	BIO01: 47.1, BIO06: 46.1, BIO07: 2.6, BIO14: 3.9, BIO17: 0.2
Zeugodacus cucumis	0.886	0.03	BIO02: 2.4, BIO11: 36.2, BIO14: 7.1, BIO17: 54.3

S2 Table. Projected changes in the area of suitable habitat for all 11 fruit fly species, under six future climate scenarios, relative to the current period. (1) *Bactrocera aquilonis* (2) *Bactrocera bryoniae* (3) *Bactrocera frauenfeldi* (4) *Bactrocera halfordiae* (5) *Bactrocera jarvisi* (6) *Bactrocera kraussi* (7) *Bactrocera musae* (8) *Bactrocera neohumeralis* (9) *Bactrocera tryoni* (10) *Ceratitis capitata* (11) *Zeugodacus cucumis*. For each species, the first column indicates the GCM (Global Climate Model) for three time periods 2030, 2050 and 2070. Other columns: % Lost refers to the percentage of currently suitable habitat projected to become unsuitable in the future; % Gained refers to the percentage of future suitable habitat that is in areas currently unsuitable; Range Changed refers to the change (%) between the size of current and future suitable habitat (positive numbers indicate an increase in range size, negative numbers indicate a decrease).

(1) *Bactrocera aquilonis*

GCM_Time period	% Lost	% Gained	% Range Changed
CanESM _30	0	80.13	403.32
CanESM _50	0	85.45	587.39
CanESM _70	0	89.37	840.48
ACCESS_30	0	68.39	216.34
ACCESS_50	0	81.25	433.38
ACCESS_70	0	86.08	618.19
GFDL_30	0	78.01	354.69
GFDL_50	0	82.61	474.93
GFDL_70	0	86.05	616.86
MIROC_30	0	67.55	208.18
MIROC_50	0	78.99	375.94
MIROC_70	0	83.03	489.30
HadGEM2_30	0	78.18	358.34
HadGEM2_50	0	84.06	527.50
HadGEM2_70	0	87.71	714.05
NorEsm_30	0	53.92	117.01
NorEsm_50	0	71.97	256.81
NorEsm_70	0	79.62	390.06

(2) *Bactorcera bryoniae*

GCM_Time period	% Lost	% Gained	% Range Changed
CanESM_30	12.95	14.19	01.43
CanESM_50	18.76	15.16	-04.23
CanESM_70	26.79	29.71	04.15
ACCESS_30	12.12	14.83	03.18
ACCESS_50	10.13	19.41	11.51
ACCESS_70	15.94	30.64	21.19
GFDL_30	14.37	15.87	01.79
GFDL_50	19.09	10.07	-10.03
GFDL_70	23.45	10.06	-14.88
MIROC_30	17.29	12.12	-05.88
MIROC_50	14.99	17.60	03.17
MIROC_70	03.59	39.19	58.52

HadGEM2_30	07.35	19.49	15.07
HadGEM2_50	06.12	20.96	18.78
HadGEM2_70	12.99	30.05	24.39
NorEsm_30	01.55	23.09	28.00
NorEsm_50	00.62	29.37	40.69
NorEsm_70	00.84	45.36	81.49

(3) *Bactrocera frauenfeldi*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	21.92	10.81	-12.46
CanESM_50	30.60	18.78	-14.56
CanESM_70	24.29	36.68	19.55
ACCESS_30	00.09	43.62	77.19
ACCESS_50	02.94	29.48	37.64
ACCESS_70	09.09	32.47	34.60
GFDL_30	02.41	14.56	14.22
GFDL_50	02.67	21.66	24.23
GFDL_70	00.00	39.45	65.13
MIROC_30	01.89	40.14	63.88
MIROC_50	09.87	34.67	37.95
MIROC_70	21.08	21.52	00.56
HadGEM_30	13.81	20.99	09.09
HadGEM_50	27.66	30.31	03.80
HadGEM_70	16.27	30.25	20.04
NorEsm_30	10.50	18.47	09.77
NorEsm_50	01.36	33.74	48.87
NorEsm_70	00.00	51.98	108.25

(4) *Bactrocera halfordiae*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	65.13	35.11	-46.27
CanESM_50	73.22	56.79	-38.03
CanESM_70	81.39	73.69	-29.26
ACCESS_30	70.09	45.93	-44.69
ACCESS_50	66.38	56.48	-22.76
ACCESS_70	52.41	58.67	15.14
GFDL_30	86.21	35.98	-78.47
GFDL_50	89.27	44.40	-80.69
GFDL_70	89.66	51.29	-78.76
MIROC_30	79.19	07.92	-77.41
MIROC_50	53.56	38.73	-24.20

MIROC_70	15.09	56.39	94.68
HadGEM2_30	51.42	28.35	-32.19
HadGEM2_50	48.04	51.83	07.85
HadGEM2_70	47.19	65.21	51.75
NorEsm_30	05.57	40.84	59.61
NorEsm_50	39.38	43.86	07.99
NorEsm_70	39.27	62.21	60.74

(5) *Bactrocera jarvisi*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	08.96	45.53	67.14
CanESM_50	10.62	45.53	82.82
CanESM_70	10.31	58.77	117.54
ACCESS_30	11.35	35.79	38.08
ACCESS_50	05.02	49.72	88.88
ACCESS_70	07.19	62.46	147.19
GFDL_30	11.09	44.18	59.26
GFDL_50	12.64	49.32	72.39
GFDL_70	10.72	55.06	98.68
MIROC_30	13.79	41.39	47.08
MIROC_50	09.70	54.00	96.32
MIROC_70	00.55	66.26	194.74
HadGEM_30	04.87	46.93	79.26
HadGEM_50	02.40	55.42	118.91
HadGEM_70	00.69	65.52	188.06
NorEsm_30	00.12	31.01	44.78
NorEsm_50	1.63E-05	44.55	80.34
NorEsm_70	00.01	64.58	182.29

(7) *Bactrocera kraussi*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	14.86	01.48	-13.58
CanESM_50	13.59	02.95	-10.96
CanESM_70	09.37	16.42	08.43
ACCESS_30	00.79	21.96	27.11
ACCESS_50	01.17	14.20	15.18
ACCESS_70	02.41	16.87	17.39
GFDL_30	04.95	05.22	00.29
GFDL_50	02.91	08.59	06.22
GFDL_70	02.27	18.89	20.51
MIROC_30	00.90	16.79	19.09

MIROC_50	04.43	13.08	09.96
MIROC_70	00.28	15.35	17.79
HadGEM2_30	07.03	11.66	05.23
HadGEM2_50	04.45	22.59	23.43
HadGEM2_70	01.65	22.25	26.50
NorEsm_30	06.52	07.89	01.49
NorEsm_50	02.43	17.23	17.88
NorEsm_70	01.41	29.61	40.06

(8) *Bactrocera musae*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	22.26	00.32	-22.01
CanESM_50	22.01	03.89	-18.85
CanESM_70	15.03	22.59	09.77
ACCESS_30	01.83	32.98	46.49
ACCESS_50	03.35	14.55	13.11
ACCESS_70	07.00	16.46	11.32
GFDL_30	11.73	07.68	-04.38
GFDL_50	03.41	11.99	09.75
GFDL_70	01.46	29.76	40.30
MIROC_30	01.37	31.25	43.47
MIROC_50	05.11	21.77	21.29
MIROC_70	04.39	15.73	13.45
HadGEM_30	20.89	17.25	-04.41
HadGEM_50	11.81	24.58	16.93
HadGEM_70	11.46	24.61	17.45
NorEsm_30	13.95	13.75	-00.23
NorEsm_50	03.26	26.72	32.01
NorEsm_70	00.16	43.55	76.87

(9) *Bactrocera neohumeralis:*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	24.16	03.68	-12.14
CanESM_50	24.12	19.95	-05.21
CanESM_70	25.39	39.59	23.50
ACCESS_30	25.19	31.29	08.88
ACCESS_50	22.88	27.91	06.98
ACCESS_70	22.27	41.41	32.66
GFDL_30	32.49	08.34	-26.34
GFDL_50	27.87	21.08	-08.60
GFDL_70	26.68	34.80	12.45
MIROC_30	23.26	32.47	13.64
MIROC_50	16.50	37.67	33.95

MIROC_70	02.51	63.15	164.59
HadGEM_30	14.33	17.85	04.28
HadGEM_50	06.11	42.29	62.69
HadGEM_70	03.43	47.89	85.33
NorEsm_30	04.71	36.27	49.52
NorEsm_50	02.44	35.39	50.99
NorEsm_70	02.84	55.22	116.97

(10) *Bactrocera tryoni:*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	30.18	17.38	-15.49
CanESM_50	37.32	23.10	-18.49
CanESM_70	33.68	31.54	-03.13
ACCESS_30	26.09	11.10	-16.87
ACCESS_50	20.25	16.71	-04.25
ACCESS_70	17.18	26.14	12.13
GFDL_30	47.89	15.71	-38.18
GFDL_50	52.52	20.29	-40.43
GFDL_70	51.22	24.18	-35.67
MIROC_30	36.04	16.22	-23.66
MIROC_50	27.59	19.56	-09.98
MIROC_70	09.15	36.86	43.89
HadGEM_30	36.71	16.73	-23.99
HadGEM_50	29.87	21.65	-10.50
HadGEM_70	14.39	27.37	17.87
NorEsm_30	16.01	16.44	00.51
NorEsm_50	15.13	20.22	06.38
NorEsm_70	06.13	40.12	56.76

(11) *Ceratitis capitata:*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	16.51	15.76	-00.89
CanESM_50	17.52	23.16	07.34
CanESM_70	17.58	40.29	38.02
ACCESS_30	10.29	17.26	08.41
ACCESS_50	15.95	35.04	29.39
ACCESS_70	17.54	52.96	75.29
GFDL_30	20.85	07.78	-14.17
GFDL_50	22.37	11.52	-12.26
GFDL_70	17.76	24.83	09.41
MIROC_30	09.37	20.46	13.95
MIROC_50	11.91	32.26	30.05
MIROC_70	17.75	53.61	77.30
HadGEM_30	19.64	09.69	-11.02
HadGEM_50	20.14	15.62	-05.35

HadGEM_70	18.41	43.79	45.18
NorEsm_30	09.71	17.67	09.67
NorEsm_50	10.73	25.38	19.64
NorEsm_70	15.19	55.48	90.52

(3) *Zeugodacus cucumis:*

GCM Time period	% Lost	% Gained	% Range Changed
CanESM_30	04.47	52.09	99.41
CanESM_50	03.43	58.08	130.34
CanESM_70	01.72	67.63	203.59
ACCESS_30	00.00	43.33	76.45
ACCESS_50	00.00	68.73	219.79
ACCESS_70	00.06	68.22	214.43
GFDL_30	08.26	44.66	65.77
GFDL_50	09.75	52.92	91.71
GFDL_70	10.32	57.65	111.77
MIROC_30	04.20	51.81	98.80
MIROC_50	00.02	57.86	137.23
MIROC_70	00.01	78.26	359.92
HadGEM2_30	05.42	51.22	93.88
HadGEM2_50	01.67	58.42	136.46
HadGEM2_70	00.00	76.09	318.29
NorEsm_30	00.97	47.51	88.66
NorEsm_50	00.60	62.77	166.97
NorEsm_70	00.08	80.39	409.58

S3 Table. Area (km²) and percentage of Australia projected to be suitable for 11 fruit flies under six future climate scenarios. In the column 'Climate scenarios', 0 refers to the area projected to be unsuitable across all six scenarios; 1 refers to the area projected to be suitable under any one of the six scenarios…6 refers to the area projected to be suitable under all six scenarios.

Species	Climate scenarios	2030 1000 km²	2030 (%)	2050 1000 km²	2050 (%)	2070 1000 km²	2070 (%)
Bactrocera aquilonis	0	6,027	78.5	5,433	70.8	4,606	60
	1	106	1.4	189	2.5	419	5.5
	2	109	1.4	178	2.3	281	3.7
	3	350	4.6	142	1.9	58	0.8
	4	129	1.7	179	2.3	387	5
	5	248	3.2	393	5.1	331	4.3
	6	704	9.2	1,159	15.1	1,592	20.7
Bactrocera bryoniae	0	6,635	86.5	6,596	86	6,093	79.4
	1	220	2.9	205	2.7	523	6.8
	2	83	1.1	104	1.4	180	2.4
	3	58	0.8	75	1	156	2
	4	50	0.7	77	1	101	1.3
	5	82	1.1	87	1.1	120	1.6
	6	546	7.1	529	6.9	498	6.5
Bactrocera frauenfeldi	0	7,423	96.7	7,434	96.9	7,366	96
	1	43	0.6	41	0.5	80	1
	2	31	0.4	27	0.3	37	0.5
	3	32	0.4	26	0.3	42	0.5
	4	16	0.2	26	0.3	23	0.3
	5	46	0.6	32	0.4	24	0.3
	6	83	1.1	87	1.1	102	1.3
Bactrocera halfordiae	0	7,146	93.1	7,191	93.7	6,917	90.1
	1	277	3.6	165	2.2	213	2.8
	2	92	1.2	89	1.2	147	1.9
	3	53	0.7	68	0.9	163	2.1
	4	45	0.6	60	0.8	101	1.3
	5	34	0.4	53	0.7	80	1
	6	26	0.3	46	0.6	52	0.7
Bactrocera jarvisi	0	5,688	74.1	5,374	70	4,274	55.7
	1	323	4.2	270	3.5	677	8.8
	2	172	2.2	196	2.6	314	4.1
	3	171	2.2	170	2.2	288	3.7
	4	129	1.7	186	2.4	280	3.7
	5	242	3.1	308	4	292	3.8
	6	948	12.4	1,169	15.2	1,549	20.2
Bactrocera kraussi	0	7,432	96.9	7,416	96.7	7,386	96.3
	1	20	0.3	29	0.4	38	0.5
	2	18	0.2	18	0.2	21	0.3
	3	16	0.2	21	0.3	19	0.3
	4	17	0.2	16	0.2	16	0.2
	5	30	0.4	28	0.4	31	0.4
	6	140	1.8	145	1.9	162	2.1
Bactrocera musae	0	7,406	96.5	7,418	96.7	7,347	95.8
	1	46	0.6	33	0.4	74	1
	2	36	0.5	27	0.4	36	0.5
	3	22	0.3	23	0.3	36	0.5
	4	22	0.3	25	0.3	25	0.3
	5	45	0.6	39	0.5	25	0.3
	6	97	1.3	109	1.4	130	1.7

Bactrocera neohumeralis	0	7,140	93	7,031	91.6	6,598	86
	1	158	2.1	193	2.5	440	5.7
	2	74	1	112	1.5	159	2.1
	3	44	0.6	41	0.5	136	1.8
	4	38	0.5	53	0.7	61	0.8
	5	50	0.7	51	0.7	70	0.9
	6	170	2.2	192	2.5	210	2.7
Bactrocera tryoni	0	5,673	73.9	5,567	72.5	4,638	60.4
	1	471	6.1	399	5.2	772	10.1
	2	175	2.3	189	2.5	291	3.8
	3	144	1.9	207	2.7	292	3.8
	4	174	2.3	245	3.2	350	4.6
	5	305	4	256	3.3	336	4.4
	6	731	9.5	810	10.6	994	13
Ceratitis capitata	0	5,501	71.7	5,104	66.5	4,056	52.9
	1	336	4.4	475	6.2	554	7.2
	2	180	2.3	321	4.2	406	5.3
	3	159	2.1	194	2.5	402	5.2
	4	206	2.7	205	2.7	474	6.2
	5	220	2.9	250	3.3	447	5.8
	6	1,070	13.9	1,123	14.6	1,334	17.4
Zeugodacus cucumis	0	6,536	85.2	6,117	79.7	4,958	64.6
	1	218	2.8	249	3.3	779	10.2
	2	123	1.6	276	3.6	424	5.5
	3	109	1.4	157	2	268	3.5
	4	76	1	99	1.3	252	3.3
	5	107	1.4	172	2.2	202	2.6
	6	504	6.6	602	7.9	790	10.3

S4 Table. Major commercial fruits and vegetables host species to the Australian Horticulture Statistics Handbook (HSHB; www.horticulture.com.au). Pest status is based on Hancock et al (2000), where "major" indicates that there have been many records of the fly infesting that host.

Fruit fly species	Scientific name	Common name	Key region	Latitude	Longitude	State	Reference	Pest status
Bactrocera aquilonis	*Capsicum annuum*	bell pepper	Bowen	-20.014	148.248	Queensland	1	major
Bactrocera aquilonis	*Capsicum annuum*	bell pepper	Bundaberg	-24.866	152.348	Queensland	1	major
Bactrocera aquilonis	*Capsicum annuum*	bell pepper	Carnarvon	-24.881	113.659	Western Australia	1	major
Bactrocera aquilonis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	1	major
Bactrocera aquilonis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	1	major
Bactrocera aquilonis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	1	major
Bactrocera aquilonis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Mareeba	-16.995	145.423	Queensland	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Burnett	-24.767	152.4	Queensland	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Bundaberg	-24.866	152.348	Queensland	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Lismore	-28.814	153.277	New South Wales	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Riverland	-34.25	140.467	South Australia	1	major
Bactrocera aquilonis	*Citrus × limon*	lemon	Darwin	-12.463	130.842	Northern Territory	1	major
Bactrocera aquilonis	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	1	major
Bactrocera aquilonis	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	1	major
Bactrocera aquilonis	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	1	major
Bactrocera aquilonis	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	1	major
Bactrocera aquilonis	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	1	major
Bactrocera aquilonis	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	1	major
Bactrocera aquilonis	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	1	major
Bactrocera aquilonis	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	1	major
Bactrocera aquilonis	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	1	major
Bactrocera aquilonis	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	1	major

Bactrocera aquilonis	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	1	major
Bactrocera aquilonis	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	1	major
Bactrocera aquilonis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	1	major
Bactrocera aquilonis	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	1	major
Bactrocera aquilonis	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	1	major
Bactrocera aquilonis	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	1	major
Bactrocera aquilonis	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	1	major
Bactrocera bryoniae	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera bryoniae	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera bryoniae	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	2	major
Bactrocera bryoniae	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	2	major
Bactrocera bryoniae	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera bryoniae	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera bryoniae	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	2	major
Bactrocera bryoniae	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	3	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	3	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	3	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	3	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	3	major
Bactrocera frauenfeldi	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	3	major

Bactrocera frauenfeldi	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	3	major
Bactrocera frauenfeldi	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	3	major
Bactrocera frauenfeldi	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	3	major
Bactrocera frauenfeldi	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	3	major
Bactrocera frauenfeldi	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	3	major
Bactrocera frauenfeldi	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	3	major
Bactrocera frauenfeldi	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	3	major
Bactrocera frauenfeldi	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	3	major
Bactrocera frauenfeldi	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	3	major
Bactrocera frauenfeldi	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	3	major
Bactrocera frauenfeldi	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	3	major
Bactrocera frauenfeldi	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	3	major
Bactrocera frauenfeldi	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	3	major
Bactrocera frauenfeldi	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	3	major
Bactrocera frauenfeldi	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	3	major
Bactrocera frauenfeldi	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	3	major
Bactrocera frauenfeldi	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	3	major
Bactrocera halfordiae	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera halfordiae	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	2	major
Bactrocera halfordiae	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	2	major
Bactrocera halfordiae	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	2	major
Bactrocera halfordiae	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	2	major
Bactrocera halfordiae	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera halfordiae	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	2	major
Bactrocera halfordiae	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	2	major

Bactrocera halfordiae	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera halfordiae	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	2	major
Bactrocera halfordiae	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera halfordiae	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	2	major
Bactrocera halfordiae	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera halfordiae	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera jarvisi	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	2	major
Bactrocera jarvisi	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera jarvisi	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	2	major
Bactrocera jarvisi	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	2	major
Bactrocera jarvisi	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	2	major
Bactrocera jarvisi	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	2	major

Bactrocera jarvisi	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	2	major
Bactrocera jarvisi	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	2	major
Bactrocera jarvisi	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	2	major
Bactrocera jarvisi	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera jarvisi	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Lockyer Valley	-27.628	152.169	Queensland	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Sydney Basin	-33.865	151.21	New South Wales	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Sunraysia	-34.204	142.135	Victoria	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Murray valley	-36.141	144.761	Victoria	2	major
Bactrocera jarvisi	*Diospyros kaki*	persimmon	Riverland	-34.25	140.467	South Australia	2	major
Bactrocera kraussi	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera kraussi	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	2,3	major
Bactrocera kraussi	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	2,3	major
Bactrocera kraussi	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	2,3	major
Bactrocera kraussi	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	2,3	major
Bactrocera kraussi	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	2,3	major
Bactrocera kraussi	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	2,3	major
Bactrocera kraussi	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	2,3	major
Bactrocera kraussi	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	2,3	major
Bactrocera kraussi	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	2,3	major
Bactrocera kraussi	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	2,3	major
Bactrocera kraussi	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	2,3	major

Bactrocera kraussi	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	2,3	major
Bactrocera kraussi	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	2,3	major
Bactrocera kraussi	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	2,3	major
Bactrocera kraussi	*Prunus persica*	peach	Tweed Valley	-28.183	153.55	New South Wales	2,3	major
Bactrocera kraussi	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	2,3	major
Bactrocera kraussi	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	2,3	major
Bactrocera kraussi	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	2,3	major
Bactrocera musae	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	2,3	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	2	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	2	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera neohumeralis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	2	major

Bactrocera neohumeralis	*Prunus persica*	peach	Tweed Valley	-28.183	153.55	New South Wales	2	major
Bactrocera neohumeralis	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	2	major
Bactrocera neohumeralis	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	2	major
Bactrocera neohumeralis	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	2	major
Bactrocera neohumeralis	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	2	major
Bactrocera neohumeralis	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera neohumeralis	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Lockyer Valley	-27.628	152.169	Queensland	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Sydney Basin	-33.865	151.21	New South Wales	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Sunraysia	-34.204	142.135	Victoria	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Murray valley	-36.141	144.761	Victoria	2	major
Bactrocera neohumeralis	*Diospyros kaki*	persimmon	Riverland	-34.25	140.467	South Australia	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	2	major

Bactrocera neohumeralis	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	2	major
Bactrocera neohumeralis	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Tully	-17.933	145.933	Queensland	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera neohumeralis	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	2	major
Bactrocera neohumeralis	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	2	major
Bactrocera neohumeralis	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	2	major
Bactrocera neohumeralis	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	2	major
Bactrocera neohumeralis	*Prunus armeniaca*	apricot	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Prunus armeniaca*	apricot	Swan Hill	-35.333	143.549	South Australia	2	major
Bactrocera neohumeralis	*Prunus armeniaca*	apricot	Renmark	-34.17	140.75	South Australia	2	major
Bactrocera neohumeralis	*Prunus armeniaca*	apricot	Perth	-31.954	115.857	Western Australia	2	major
Bactrocera neohumeralis	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	2	major
Bactrocera neohumeralis	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	2	major
Bactrocera neohumeralis	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	2	major
Bactrocera neohumeralis	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera neohumeralis	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	2	major
Bactrocera neohumeralis	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	2	major
Bactrocera neohumeralis	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	2	major
Bactrocera neohumeralis	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	2	major
Bactrocera neohumeralis	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	2	major
Bactrocera neohumeralis	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	2	major
Bactrocera neohumeralis	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	2	major
Bactrocera neohumeralis	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera neohumeralis	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	2	major

Bactrocera neohumeralis	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	2	major
Bactrocera neohumeralis	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	2	major
Bactrocera neohumeralis	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	2	major
Bactrocera neohumeralis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	2	major
Bactrocera neohumeralis	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera neohumeralis	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	2	major
Bactrocera neohumeralis	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	2	major
Bactrocera neohumeralis	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	2	major
Bactrocera neohumeralis	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	2	major
Bactrocera neohumeralis	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	2	major
Bactrocera tryoni	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	2,5	major
Bactrocera tryoni	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	2,5	major
Bactrocera tryoni	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	2,5	major
Bactrocera tryoni	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	2,5	major
Bactrocera tryoni	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Tully	-17.933	145.933	Queensland	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Lakeland	-15.817	145	Queensland	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	2,5	major
Bactrocera tryoni	*Musa × paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Yarra Valley	-37.733	145.683	Victoria	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Beerwah	-26.899	152.883	Queensland	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Camden	-34.054	150.695	New South Wales	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Adelaide Hills	-34.911	138.707	South Australia	2,5	major

Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Wanneroo	-31.746	115.823	Western Australia	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Bullsbrook	-31.663	116.029	Western Australia	2,5	major
Bactrocera tryoni	*Fragaria × ananassa*	strawberry	Albany	-35.027	117.884	Western Australia	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	2,5	major
Bactrocera tryoni	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Lockyer Valley	-27.628	152.169	Queensland	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Sydney Basin	-33.865	151.21	New South Wales	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Sunraysia	-34.204	142.135	Victoria	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Goulburn Valley	-37.034	145.125	Victoria	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Murray valley	-36.141	144.761	Victoria	2,5	major
Bactrocera tryoni	*Diospyros kaki*	persimmon	Riverland	-34.25	140.467	South Australia	2,5	major
Bactrocera tryoni	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	2,5	major
Bactrocera tryoni	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	2,5	major
Bactrocera tryoni	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	2,5	major
Bactrocera tryoni	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	2,5	major
Bactrocera tryoni	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	2,5	major
Bactrocera tryoni	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	2,5	major
Bactrocera tryoni	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	2,5	major
Bactrocera tryoni	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	2,5	major

Bactrocera tryoni	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	2,5	major
Bactrocera tryoni	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	2,5	major
Bactrocera tryoni	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Tully	-17.933	145.933	Queensland	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Bundaberg	-24.866	152.348	Queensland	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	2,5	major
Bactrocera tryoni	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	2,5	major
Bactrocera tryoni	*Prunus persica*	peach	Tweed Valley	-28.183	153.55	New South Wales	2,5	major
Bactrocera tryoni	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	2,5	major
Bactrocera tryoni	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	2,5	major
Bactrocera tryoni	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	2,5	major
Bactrocera tryoni	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	2,5	major
Bactrocera tryoni	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	2,5	major
Bactrocera tryoni	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	2,5	major
Bactrocera tryoni	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	2,5	major
Bactrocera tryoni	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	2,5	major
Bactrocera tryoni	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	2,5	major
Bactrocera tryoni	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	2,5	major

Bactrocera tryoni	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	2,5	major
Bactrocera tryoni	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	2,5	major
Bactrocera tryoni	*Prunus persica var. nucipersica*	nectarine	Stanthorpe	-28.667	151.95	Queensland	2,5	major
Bactrocera tryoni	*Prunus persica var. nucipersica*	nectarine	Sunraysia	-34.204	142.135	Victoria	2,5	major
Bactrocera tryoni	*Prunus persica var. nucipersica*	nectarine	Orange	-33.284	149.101	New South Wales	2,5	major
Bactrocera tryoni	*Prunus persica var. nucipersica*	nectarine	Young	-34.314	148.298	New South Wales	2,5	major
Ceratitis capitata	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	2,4,5	major
Ceratitis capitata	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	2,4,5	major
Ceratitis capitata	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	2,4,5	major
Ceratitis capitata	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	2,4,5	major
Ceratitis capitata	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	2,4,5	major
Ceratitis capitata	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	2,4,5	major
Ceratitis capitata	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	2,4,5	major
Ceratitis capitata	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	2,4,5	major
Ceratitis capitata	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	2,4,5	major
Ceratitis capitata	*Prunus persica*	peach	Tweed Valley	-28.183	153.55	New South Wales	2,4,5	major
Ceratitis capitata	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	2,4,5	major
Ceratitis capitata	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	2,4,5	major
Ceratitis capitata	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	2,4,5	major

Ceratitis capitata	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	2,4,5	major
Ceratitis capitata	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	2,4,5	major
Ceratitis capitata	*Citrus × paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	2,4,5	major
Ceratitis capitata	*Citrus × paradisi*	grapefruit	Riverina	-35	146	New South Wales	2,4,5	major
Ceratitis capitata	*Citrus × paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	2,4,5	major
Ceratitis capitata	*Citrus × paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	2,4,5	major
Ceratitis capitata	*Citrus × paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	2,4,5	major
Ceratitis capitata	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	2,4,5	major
Ceratitis capitata	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	2,4,5	major
Ceratitis capitata	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	2,4,5	major
Ceratitis capitata	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	2,4,5	major
Ceratitis capitata	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	2,4,5	major
Ceratitis capitata	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	2,4,5	major
Ceratitis capitata	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	2,4,5	major
Ceratitis capitata	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	2,4,5	major
Zeugodacus cucumis	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	2	major
Zeugodacus cucumis	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	2	major
Zeugodacus cucumis	*Cucumis sativus*	cucumber	Bowen	-20.014	148.248	Queensland	2	major
Zeugodacus cucumis	*Cucumis sativus*	cucumber	Bundaberg	-24.866	152.348	Queensland	2	major
Zeugodacus cucumis	*Cucumis sativus*	cucumber	Riverland region	-34.25	140.467	South Australia	2	major
Zeugodacus cucumis	*Cucurbita moschata*	pumpkin	Murrumbidgee region	-34.8	145.883	New South Wales	2	major
Zeugodacus cucumis	*Cucurbita moschata*	pumpkin	Bundaberg	-24.866	152.348	Queensland	2	major
Zeugodacus cucumis	*Cucurbita moschata*	pumpkin	Darling Downs region	-27.5	151.265	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Atherton Tablelands	-17.371	145.403	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Bowen	-20.014	148.248	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Bundaberg	-24.866	152.348	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Bathurst	-33.417	149.581	New South Wales	2	major

Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Sunraysia region	-34.204	142.135	Victoria	2	major
Zeugodacus cucumis	*Cucurbita pepo*	zucchini	Perth	-31.954	115.857	Western Australia	2	major
Zeugodacus cucumis	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	2	major
Zeugodacus cucumis	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	2	major
Zeugodacus cucumis	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	2	major
Zeugodacus cucumis	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	2	major
Zeugodacus cucumis	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	2	major
Zeugodacus cucumis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	2	major
Zeugodacus cucumis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	2	major
Zeugodacus cucumis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	2	major
Zeugodacus cucumis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	2	major
Zeugodacus cucumis	*Cucurbita pepo*	squash/zucchini	Atherton Tablelands	-17.371	145.403	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	squash/zucchini	Bowen	-20.014	148.248	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	squash/zucchini	Bundaberg	-24.866	152.348	Queensland	2	major
Zeugodacus cucumis	*Cucurbita pepo*	squash/zucchini	Bathurst	-33.417	149.581	New South Wales	2	major
Zeugodacus cucumis	*Cucurbita pepo*	squash/zucchini	Sunraysia region	-34.204	142.135	Victoria	2	major

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5 May, A. W. S. An investigation of fruit flies (Trypertidae: Diptera) in Queensland 1. Introduction, species, pest status and distribution. *Queensland Journal of Agricultural Science* **20**, 1-82 (1963).

S5 Table. DOIs for GBIF occurrence records

1.	DOI: http://doi.org/10.15468/dl.kvaecc Creation Date: Thursday, June 29, 2017 4:59:20 AM CEST Filter used: TaxonKey: *Bactrocera bryoniae* (Tryon, 1927)
2.	DOI: http://doi.org/10.15468/dl.7ll9me Creation Date: Monday, July 3, 2017 12:22:56 PM CEST Filter used: TaxonKey: *Bactrocera kraussi* (Hardy, 1951)
3.	DOI: http://doi.org/10.15468/dl.tyaphx Creation Date: Wednesday, June 28, 2017 4:55:59 PM CEST Filter used: TaxonKey: *Bactrocera aquilonis* (May, 1965)
4.	DOI: http://doi.org/10.15468/dl.q4mv6v Creation Date: Wednesday, June 28, 2017 5:59:09 PM CEST Filter used: TaxonKey: *Bactrocera cucumis* (French, 1907)
5.	DOI: http://doi.org/10.15468/dl.re8do1 Creation Date: Thursday, June 29, 2017 4:31:49 AM CEST Filter used: TaxonKey: *Bactrocera frauenfeldi* (Schiner, 1868) or *Bactrocera cucumis* (French, 1907) or *Bactrocera halfordiae* (Tryon, 1927) or *Bactrocera jarvisi* (Tryon, 1927)
6.	DOI: http://doi.org/10.15468/dl.tyll13 Creation Date: Thursday, June 29, 2017 4:43:53 AM CEST Filter used: TaxonKey: *Bactrocera jarvisi* (Tryon, 1927)
7.	DOI: http://doi.org/10.15468/dl.vvaofg Creation Date: Tuesday, July 4, 2017 3:07:55 AM CEST Filter used: TaxonKey: *Bactrocera halfordiae* (Tryon, 1927)
8.	DOI: http://doi.org/10.15468/dl.iqifxg Creation Date: Tuesday, July 4, 2017 3:23:43 AM CEST Filter used: TaxonKey: *Bactrocera musae* (Tryon, 1927)
9.	DOI: http://doi.org/10.15468/dl.drca1h Creation Date: Tuesday, July 4, 2017 3:33:43 AM CEST Filter used: TaxonKey: *Bactrocera neohumeralis* (Hardy, 1951)
10.	DOI: http://doi.org/10.15468/dl.cuhilk Creation Date: Friday, July 14, 2017 6:45:42 AM CEST Filter used: TaxonKey: *Ceratitis capitata* (Wiedemann, 1824)

CHAPTER FOUR

Estimating the current and future risk of exotic fruit fly species establishing in Australia

Abstract

Of the 46 native and non-native tephritid fruit fly pests that have been identified as presenting an economic threat to the Australian horticultural industry, 19 are currently absent from this continent. However, their geographic proximity to Australia and/or their status elsewhere as pests of horticultural industries that are also present in Australia, have led to their identification as 'high priority pests'. To date, the likelihood of these species establishing in Australia under future climate change has not be explored. The goal of this chapter is to undertake climate matching for these 19 species and to assess how their relative establishment likelihoods (EL) may change due to shifts in climate. To do so, I combined maps of regions of Australia with a climate similar to species' known ranges, under current and future climates, with a key arrival pathway (i.e. the movement of people entering Australia from host countries) and the distribution of host plants, to estimate species relative ELs. I found that *Bactrocera dorsalis* has the highest EL under all climate scenarios, followed by *Zeugodacus cucurbitae* and *B. latifrons*, while *B. occipitalis* and *Rhagoletis indifferens* consistently have the lowest EL. As the century progresses, the ranking of the species generally remains stable. However, the EL of *Anastrepha ludens*, *B. carambolae* and *Toxotrypana curvicauda* increases considerably. In contrast, EL of all three *Rhagoletis* species is projected to decline. My findings are valuable for the horticultural industry as well as pest managers, as it enables appropriate ongoing surveillance and management strategies to be planned and initiated.

Keywords: climate change, ExDet, horticulture, non-native fruit fly, relative establishment likelihood, risk assessment

Introduction

The introduction and spread of invasive species is one of the most critical threats to natural systems, agriculture, and forestry globally (Mack et al. 2000, Pimentel et al. 2000). These species can cause significant economic impacts. In the United States, invasive species have been estimated to cause US$137 billion dollars in damage and losses to crops and forests annually (Pimentel et al. 2001), and collectively more than $314 billion per annum in the USA, United Kingdom, Australia, South Africa, India and Brazil (Colautti et al. 2006). Within Europe, the cost of invasive species has been estimated at €12.5–20 billion annually (Kettunen et al. 2008, Roques et al. 2009).

Invasive species are likely to be impacted both directly and indirectly as a result of climate change (Mooney and Hobbs 2000). As climate zones shift, so too will the suitability of a region for a given species. Thus, climate change may alter the movement, introduction, establishment and spread of invasive species (Plant Health Australia 2008, Gallardo et al. 2019). As a result, the effectiveness of existing monitoring and control strategies may be impacted (Hellmann et al. 2008). It is therefore necessary for risk assessments to incorporate potential responses of species to climate change.

Tephritidae fruit flies as pests

Tephritid fruit flies are among the world's most devastating horticultural pests, with prominent examples including *Bactrocera dorsalis* (Oriental fruit fly), *B. latifrons* (Solanum fruit fly), *Ceratitis capitata* (Mediterranean fruit fly) *Anastrepha ludens* (Mexican fruit fly) and *Zeugodacus cucurbitae* (Melon fly) (Bateman 1972, White and Elson-Harris 1992, Clarke et al. 2005, Aluja and Mangan 2008, Papadopoulos et al. 2013, Karsten et al. 2015). Tephritids cause severe damage to fruits and vegetables, resulting in losses in the quality and quantity of produce (Duyck et al. 2004, De Meyer et al. 2008). The transport of produce within and between countries has facilitated the invasion of many tephritid species (Hill et al. 2016) despite major efforts to control their movement (Duyck et al. 2004, Papadopoulos et al. 2013). For example, the movement of fruit via baggage of air passengers has been shown as a major invasion pathway (Liebhold et al. 2006, Ma et al. 2012), with ~170 interceptions of *C. capitata* at Los Angeles and Miami International Airports from 1984 to 2000 (Liebhold et al. 2006). In Florida, 69% of organisms seized were on flights from South and Central America, and ~62%

of the total were associated with passenger baggage (Szyniszewska et al. 2016). Similarly, from 2003 to 2008, Chinese quarantine authorities intercepted *B. latifrons* 2156 times, most of which were transported by air passengers carrying fruits (Ma et al. 2012).

Horticulture is Australia's third largest agricultural industry, with a total production value of $9.8 billion over the year 2015-2016 (Plant Health Australia 2015). To date, 46 species of fruit fly, both native and non-native, have been identified as presenting an economic threat to the Australian horticulture industry (Plant Health Australia 2017). Of these, 19 species (Table 1) are currently absent from Australia, but could significantly impact production and trade should populations be established (Plant Health Australia 2017). Several studies have demonstrated that climatically suitable habitat for some of these species exists in Australia, with climate change likely to alter habitat suitability (Stephens et al. 2007, Hill et al. 2016, Stephens et al. 2016). However, to date there has not been an assessment of the relative likelihood of establishment of these 19 species within Australia under current and potential future climates. As such, here I assess relative likelihoods given the climatic similarity of Australia to species' known ranges, and the spatial congruence with regions of Australia that are likely to a) be within reach of international air passengers arriving from countries with known populations of these species and b) contain commercial host plant species. I then assess how establishment likelihoods may change as a result of climate change.

Table 1. Nineteen non-native invasive tephritid fruit fly species considered "High Priority Pests" for Australia (Plant Health Australia 2017).

Species	Common name	Current distribution*	Commercial hosts**	Industry for which species is a high priority pest***
Anastrepha ludens (Loew, 1873)	Mexican fruit fly	Texas, United States, south through Mexico to Costa Rica	Citrus, mango, peach	Citrus
Bactrocera carambolae (Drew and Hancock, 1994)	Carambola fruit fly	Southern Thailand, Peninsular Malaysia, East Malaysia, Kalimantan (Borneo), Singapore, Indonesian islands east to Sumbawa, Andaman Islands, Surinam, French Guyana, Guyana	Carambola, guava and mango.	Avocado, tomato, citrus, mango, papaya, passionfruit, viticulture
Bactrocera dorsalis (Hendel, 1912) (NB. *B. invadens*, *B. papaya*, *B. philippinensis* are synonyms)	Oriental fruit fly	India, Sri Lanka, Nepal, Bhutan, Myanmar, southern China, Taiwan, Hong Kong, northern and central Thailand, Vietnam, Cambodia, Laos, Hawaii, Mariana Islands, Tahiti	Bell pepper, pawpaw, mandarin, persimmon, apple, mango, banana, apricot, plum, peach, guava	Apple, pear, avocado, tomato, citrus, lychee, papaya, passionfruit, summerfruit, viticulture, melon, mango
Bactrocera facialis (Coquillett, 1909)	Tropical fruit fly	Known from the Tongatapu I. and the Ha'apai Group, Tonga	Avocado, bell pepper, citrus, guava, tomato and others	Avocado, tomato, passionfruit

Bactrocera kandiensis (Drew & Hancock, 1994)	-	Confined to Sri Lanka	Mango, carambola, guava, papaya	Avocado, citrus, passionfruit
Bactrocera kirki (Froggatt, 1911)	-	Widespread in the South Pacific Islands: Western Samoa, American Samoa, Tonga, Niue and Tahiti	Mango, apricot, banana, guava, peach, pear, persimmon and others	Avocado, passionfruit
Bactrocera latifrons (Hendel, 1915)	Solanum fruit fly	Sri Lanka, India, Pakistan through to Southern China, Japan, Taiwan, Thailand, Laos, Vietnam, Peninsular Malaysia, Indonesia, Hawaii, Tanzania	Chilli, tomato and melon	Melon
Bactrocera melanotus (Coquillett, 1909)	-	Restricted to Cook Island	Mango, guava, avocado, passionfruit, citrus	Avocado, passionfruit
Bactrocera occipitalis (Bezzi, 1919)	-	Philippines and Borneo (East Malaysian Sabah), Brunei, Indonesian Kalimantan)	Mango, guava	Citrus
Bactrocera oleae (Rossi, 1790)	Olive fruit fly	South and Central Africa, Pakistan, Mediterranean Europe and the Middle East and it has been introduced recently to California, USA, and Mexico	Olives	Olives
Bactrocera passiflorae (Froggatt, 1911)	Fijian fruit fly	Fiji Islands, Niue, Wallis and Futuna	Mango, papaya, guava, coffee, citrus, star apple and chilli	Papaya, avocado, passionfruit
Bactrocera psidii (Froggatt, 1899)	South sea guava fruit fly	Restricted to New Caledonia	Citrus, mango, guava	Passionfruit
Bactrocera trivialis (Drew, 1971)	New Guinea fruit fly	Mainland Papua New Guinea, Indonesia (Papua, West Papua)	Chilli, grapefruit, peach, guava	Citrus
Bactrocera xanthodes (Broun, 1904)	Pacific fruit fly	Fiji Islands, Tonga, Niue, Vanuatu, Samoa, American Samoa, Southern group of Cook Islands, Wallis and Futuna, French Polynesia	Bell pepper, citrus, guava, papaya, tomato, pawpaw	Avocado, passionfruit
Rhagoletis pomonella (Walsh, 1867)	Apple maggot	Canada, United States and Mexico	Apple	Apple, pear, cherry
Rhagoletis fausta (Osten Sacken, 1877)	Black cherry fruit fly	Widespread occurrence in western and eastern North America (United States and Canada)	Cherry	Cherry
Rhagoletis indifferens (Curran, 1932)	Western cherry fruit fly	Western North American species (Canada and United States), Switzerland	Cherry	Cherry
Toxotrypana curvicauda (Gerstaecker, 1860)	Papaya fruit fly	Caribbean, Belize, Costa Rica, Guatemala, Honduras, Mexico, Panama, Columbia, Venezuela, USA	Pawpaw, mango	Pawpaw
Zeugodacus cucurbitae (Coquillett (1899)	Melon fruit fly	Middle East, Indian subcontinent, Southeast Asia and southern China. In Africa, it occurs in Senegal, Gambia, Guinea – Bissau, Guinea, Sierra Leone, Liberia, Ivory Coast, Mali, Burkina Faso, Ghana, Togo, Benin, Nigeria, Cameroon, Democratic Republic of the Congo, Malawi, Tanzania, Burundi, Kenya, Uganda, Ethiopia and Sudan. It is also distributed in Christmas Island, Papua New Guinea, Mariana Islands, Solomon Islands, Nauru, Kiribati, Guam, Hawaii.	Melon, giant pumpkin	Melon, avocado, tomato, papaya, summerfruit, passionfruit vegetable

* Le Roux and Mukerji 1963, Plant Health Australia 2011, 2018
** The Australian Horticulture Statistics Handbook 2017/18
*** High priority pests are those assessed to pose a particular threat to a particular plant industry during biosecurity plan in Australia.

Materials and Methods

In calculating relative likelihoods of establishment for the study species, I modified a framework developed by Camac et al. (2019), which combines information on climate suitability, host plant distribution, and air passenger movement. It was not possible to calculate absolute likelihoods of establishment, since pest interception data that describe rates of leakage through the biosecurity system were unavailable. Relative rates are reported instead, permitting ranking of the species.

Species occurrence data

I collected occurrence records for the 19 species from online databases, literature, and trap data. The databases included the Global Biodiversity Information Facility (GBIF, https://www.gbif.org, accessed 7th February, 2019), CABI Invasive Species Compendium (CABI 2019, www.cabi.org/isc.), the European and Mediterranean Plant Protection Organization (EPPO), the Australian Plant Pest Database (APPD; http://www.planthealthaustralia.com.au/resources/australian-plant-pest-database, accessed 8th March, 2019) and the Atlas of Living Australia (ALA; http://www.ala.org.au, accessed 8th March, 2019). After downloading data from these five sources, I undertook several steps to clean records: for records from ALA and GBIF, I applied filters to restrict records to those that were resolved to species level, were dated no earlier than 1 January 1950, contained valid geographic coordinates, and were not duplicates.

I also gathered occurrence records from published articles, reports and books, including (Le Roux and Mukerji 1963, Drew and Bateman 1982, Chao and Ming 1986, Aluja et al. 1987, White and Elson-Harris 1992, Liquido et al. 1994, Aluja et al. 1996, Allwood 1997, Allwood and Leblanc 1997, Amice and Sales 1997, Armstrong and Jang 1997, Drew and Romig 1997, Hamacek 1997, Heimoana et al. 1997, Hollingsworth et al. 1997, Leblanc and Allwood 1997, Leweniqila et al. 1997a, Leweniqila et al. 1997b, Purea et al. 1997, Tenakanai 1997, Vijaysegaran 1997, Vueti et al. 1997, Hancock et al. 2000, Clarke et al. 2001, Stephens et al. 2007, Satarkar et al. 2009, Mwatawala et al. 2010, Plant Health Australia 2011, Yee et al. 2011, Dowell and Penrose 2012, Ma et al. 2012, Wan et al. 2012, Malheiro et al. 2015, Vargas et al. 2015, Yee et al. 2015, Marchioro 2016, Royer et al. 2016, Royer et al. 2018, Zeng et al. 2019).

Some records from CABI and EPPO, as well as from many of the published sources listed above, included locality descriptions but not coordinates. For these, I used Google Maps (http://maps.google.com/) to georeference records at the region/locality level. Records that lacked geographic data were omitted from our study.

Recently, three *Bactrocera* species (*B. invadens*, *B. papaya* and *B. phillipinensis*) were declared as synonyms of *B. dorsalis* (Drew and Romig 2013, Schutze et al. 2015). Therefore, I combined occurrences recorded against these taxon names with those of *B. dorsalis*.

Current climate data

For baseline ('current') climatic conditions (1960-1990) I downloaded 19 bioclimatic variables from the WorldClim database (Hijmans et al. 2005) (http://www.worldclim.org/) on a 30 arc-second resolution grid. These variables represent monthly, seasonal and annual conditions. From the 19 variables, I selected six that are reflective of average and extreme hydrothermal conditions: annual mean temperature, maximum temperature of the warmest month, minimum temperature of the coldest month, annual precipitation, precipitation of the wettest quarter and precipitation of the driest quarter. I chose these variables as predictors based on the fruit flies' biology and ecological requirements, and similar habitat suitability studies undertaken on other fruit fly species (De Meyer et al. 2008, Hill et al. 2016).

Future climate data

Multiple climate scenarios should be used for impacts assessments to appropriately reflect the breadth of variability across alternate scenarios (Beaumont et al. 2008, Khanum et al. 2013). Eight global climate models (GCMs) have been identified as useful for Australian climate impact assessments (CSIRO & BoM 2015). Data representing statistically downscaled anomalies applied to the WorldClim 1.4 baseline were available for six of these GCMs from the CCAFS GCM Data Portal (http://www.ccafs-climate.org/data_spatial_downscaling/), at a spatial resolution of 30 arc seconds. The GCMs included: CanESM2, ACCESS1.0, MIROC5, HadGEM2-CC, NorESM1-M and GFDL-ESM2M. I downloaded the data for each of these models for 2030, 2050 and 2070, under the Representative Concentration Pathway 8.5 (RCP8.5; radiative forcing exceeding 8.5 Wm^{-2} by 2100) (Moss et al. 2010). I elected to use this RCP, as it is the pathway that emissions are currently most closely tracking (Peters et al. 2012). After downloading, all climate data were reprojected to a spatial resolution of 1 × 1 km (Australian Albers Equal Area, EPSG: 3577) using bilinear interpolation. This step was undertaken in R version 3.1.2 (R Core Team 2017) using the gdalwarp function in the gdalUtils package (Greenberg and Mattiuzzi 2015).

Similar and novel climate evaluation by ExDet

Novel climate space can occur when the values of individual climate variables within the projection region (here, Australia) lie beyond the values within the reference region (here, the model-fitting environmental conditions, i.e., the environments at the occurrence and background locations), or when the correlation between variables differs across these two regions. I used the ExDet tool (Extrapolation Detection, Mesgaran et al. 2014) to measure environmental similarity and novelty, based on the Mahalanobis distance (Mahalanobis 1936). ExDet also identifies and maps the environmental variables that most strongly influence novelty (Mesgaran et al. 2014).

ExDet quantifies two types of novelty, defined as Type 1 and Type 2 novelty. Type 1 novelty occurs in areas that are outside the range of individual covariates, whereas Type 2 exists where individual covariates are within the univariate range but where there are novel combinations of covariates (Mesgaran et al. 2014). While the more widely known alternative, MESS (multivariate environmental similarity surfaces; Elith et al. 2010), identifies Type 1 novelty, ExDet's detection of novel covariate correlations represents a key advance. ExDet calculates a similarity score for each location (i.e. grid cell) of interest, with negative values assigned to areas with Type 1 novelty, and values greater than 1 assigned to areas with Type 2 novelty. More extreme values represent greater dissimilarity to the reference climate, while values between 0 and 1 are considered similar to the reference climate (Mesgaran et al. 2014). Novelty was calculated under current climate and under the six future climate scenarios for each of the three periods. For each of these, binary similarity maps were then developed, where grid cells containing novel conditions were given the value of 0 and those with climate similar to the species' known range were given the value of 1.

Major commercial fruit and vegetable hosts

For each of the 19 non-native fruit fly species, I obtained information on the major commercial fruit and vegetable hosts on which infestation has been recorded. For this purpose, major host species were defined as those reported in the following sources: Australian Horticulture Statistics Handbook 2017/2018, Le Roux and Mukerji 1963, White and Elson-Harris 1992, Vijaysegaran 1997, Allwood et al. 1999, Hancock et al. 2000, Vargas et al. 2015, Plant Health Australia 2018, and the Australian Horticulture Statistics Handbook 2017/2018 (HSHB, 2018; www.horticulture.com.au). To determine the area of Australia within which host plants are likely grown, the Australian Land Use and Management (ALUM) Classification Version 8 was downloaded (http://www.agriculture.gov.au/abares/aclump/land-use/alum-classification, ABARES 2016). This resource maps land use across Australia at a spatial resolution of 50 m × 50 m, with tertiary-level data providing information on commodities. For each fruit fly species, tertiary classes representative of their commercial host plants were identified (S4 Table), then the ALUM data were aggregated to 1 km × 1 km. In doing so, the data were binarised following Camac et al. 2019, giving grid cells a value of 1 if they contained at least one 50 m × 50 m cell with a tertiary class applicable for that species, and a value of 0 to all other cells.

Arrival of air passengers from host countries

Annual data on air passengers arriving in Australia is available from International Airline Activity (Department of Infrastructure, Transport, Cities and Regional Development-BITRE, https://www.bitre.gov.au/about/index.aspx), and includes information on the monthly maximum number of passenger seats flown for each route to Australia. For each species, the annual volume of passenger seats flown to Australia from countries in which the fruit fly species is known to occur was extracted and averaged over the period 2016 to 2018.

Subsequently, the likely dispersal of these passengers across the country at a 1 km × 1 km resolution was mapped. To do so, it was assumed that the volume of passengers is proportional to the number of seats flown from those countries. Passenger volume was split into tourists and returning residents, as these two groups likely disperse differently upon arrival. Based on data from the Australian Bureau of Statistics (ABS) (https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3401.0Jul%202019, accessed 2nd October, 2019) averaged over 2016-2018, a ratio of 46% tourists to 54% residents was used and was assumed to be constant across source countries. Following Camac et al. 2019, tourist volume was then distributed across Australia based on distance from international airports (with a negative exponential distance-decay function ensuring ~50% of tourists remained within 200 km of these airports) and density of tourist accommodation. Returning resident volume was distributed in proportion to population density with no distance penalty. Spatial datasets describing tourist rooms (derived from Tourist Accommodation, 2015-16, produced by ABS; www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8635.02015-16, accessed 2nd October 2019) population density (derived from the 2016 Australian Census of Population and Housing produced by ABS; www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/2074.02016, accessed 2nd October 2019) and distance to major international airports were provided by J. Camac (see Acknowledgements), with additional details regarding their derivation given in Camac et al. 2019. Finally, the distribution of total relative passenger volume was calculated by summing the volumes of tourists and returning residents, but giving tourists twice the weight of residents to reflect an assumption that tourists are less concerned about Australian biosecurity (Camac et al. 2019).

Relative likelihoods of establishment (EL) for each species

Assuming that the proportion of passengers transporting each species and the proportion of quarantine interceptions are constant, the likelihood of establishment (EL) for a given species in each grid cell under current or future climate was quantified as:

EL = climate similarity (0/1) × host presence (0/1) × relative passenger volume (continuous)

Finally, EL was summed across all Australian cells to calculate total relative establishment likelihood. In calculating these relative likelihoods, I rescaled EL for each species such that the species with the highest EL under current climate was given a value of 1 and all others were scaled accordingly.

Results

Climate Matching

For two species (*Bactrocera facialis* and *B. psidii*) insufficient occurrence records were available to undertake climate matching (i.e. < 5 records). For six of the remaining 17 species *B. kandiensis*, *B. kirki*, *B. melanotus*, *B. passiflorae*, *B. trivialis*, *B. xanthodes*), no areas within Australia had climate matching that of their known ranges (native and invasive). However, most of these species have < 20 occurrence records, while *B. trivialis* has < 30 (S1 table).

For three species, much of the continent has similar climatic conditions to their known ranges (*B. dorsalis* [83%], *B. oleae* [92%], and *Zeugodacus cucurbitae* [99%]), while for eight species (*Anastrepha ludens*, *B. carambolae, B. latifrons*, *Rhagoletis fausta, R. indifferens, R. pomonella. T. curvicauda and Zeugodacus cucurbitae)* < 25% (and as low as < 1%) of the continent has similar climate (S1 Table). Univariate novelty (Type 1 novelty) is driven by total precipitation of the wettest month and maximum temperature of the warmest month, whereas annual mean temperature, minimum temperature of coldest month and maximum temperature of warmest month contributed to Type 2 novelty (novel combinations of variables).

Future climate

Australia is likely to continue to lack similar climate space for the six species for which there is currently no climate similarity between their known ranges and this continent. Of the remaining 11 species, the proportion of the continent with matching climate is likely to decline for six species (S1 Table). However, an increase in the area experiencing matching climates is projected for *B. dorsalis*, *B. latifrons*, *B. occipitalis, T, curvicauda and Z. cucurbitae* under at least one of the six climate scenarios (S1 Table). For *B. dorsalis*, this represents a potential increase from 83% of the continent under current conditions to 91% by 2050, although declining again to 85% by 2070. Maximum temperature of the warmest month, minimum temperature of the coldest month and precipitation of the wettest month contributed the most to Type 1 novelty, whereas annual mean temperature, minimum temperature of coldest month and maximum temperature of warmest month contributed to Type 2 novelty (novel combinations of variables).

Host plants, passengers and host countries

The area of Australia in which host plants are likely to be growing (S3 Table and S4 Table) ranged from 0.03% (*B. oleae*) to 1.77% (*B. dorsalis*) (S5 Table). Host plants for all *Rhagoletis* species combined covered only 0.25% of the country (S5 Table).

The BITRE data contains information on flights from 24 countries in which at least one of the 19 fly species occur (S6 Table). The number of passengers per year, averaged over 2016-2018, ranged from 364 (Foelkel et al. 2017) to > 3,600,000 (Singapore) (S6 Table). The two countries with the highest richness of these species are Indonesia (*B. carambolae, B. dorsalis, B. latifrons, B. occipitalis, B. trivialis* and *Z. cucurbitae*) and USA (*A. ludens, B. oleae, R. fausta, R. indifferens, R. pomonella* and *T. curvicauda*), with six species each. More than 1,870,000 passengers arrive in Australia from each of these countries annually (S6 Table).

Establishment likelihood under current and future climates

I estimated establishment likelihood (EL) for the 11 species for which parts of Australia had matching climates (now or in the future) to the species' known ranges. Of these, EL was highest for *B. dorsalis*, followed by *Z. cucurbitae* (77.5% as likely as *B. dorsalis*) and *B. latifrons* (54.7% as likely). *Bactrocera occipitalis* and *R. indifferens* had the lowest EL under all climate scenarios (Table 2). As the century progresses, the ranking of species remains stable. However, the EL of all three *Rhagoletis* species is projected to decline substantially (Table 3). In contrast, EL of *A. ludens*, *T. curvicauda*, and *B. carambolae* increases considerably (Table 3).

Table 2. Relative establishment likelihood of 11 non-native fruit fly species across Australia, relative to Bactrocera dorsalis, which was estimated as having the highest establishment likelihood. Data are based on climate matching for current conditions and three future time periods, the distribution of land uses compatible with host plant horticulture, and arrival and dispersal of passengers travelling from other countries where the species is either endemic or non-native.

Species	Current	2030	2050	2070
Bactrocera dorsalis	100.0	100.0	100.0	100.0
Zeugodacus cucurbitae	77.5	78.0	78.0	77.7
Bactrocera latifrons	54.7	55.6	56.1	56.6
Anastrepha ludens	6.9	9.7	10.9	12.0
Toxotrypana curvicauda	1.5	2.0	2.3	2.8
Bactrocera carambolae	1.0	1.4	1.5	2.7
Rhagoletis fausta	0.5	0.2	0.1	0.0
Rhagoletis pomonella	0.4	0.3	0.3	0.2
Bactrocera oleae	0.2	0.2	0.2	0.2
Rhagoletis indifferens	<0.1	<0.1	<0.1	<0.1
Bactrocera occipitalis	<0.1	<0.1	<0.1	<0.1

Table 3. Relative establishment likelihood (EL) of 11 non-native fruit fly species across Australia under current conditions, and the percent change in EL in the future, averaged over six climate scenarios for each time period. Data are based on climate matching for current conditions and three future time periods, the distribution of land uses compatible with host plant horticulture, and arrival and dispersal of passengers travelling from other countries where the species is either endemic or non-native.

		Percent change in EL		
Species	**Current EL**	**2030**	**2050**	**2070**
Bactrocera dorsalis	2589746	-0.6	-1.0	-1.3
Zeugodacus cucurbitae	2007628	0.0	-0.4	-1.0
Bactrocera latifrons	1417258	1.0	1.4	2.2
Anastrepha ludens	177593	41.1	57.1	72.3
Toxotrypana curvicauda	39044	34.0	53.6	83.4
Bactrocera carambolae	27064	28.8	38.3	153.1
Rhagoletis fausta	12292	-64.0	-82.0	-92.1
Rhagoletis pomonella	10153	-20.0	-30.9	-54.2
Bactrocera oleae	4289	0.2	0.4	0.3
Rhagoletis indifferens	679	-89.1	-96.8	-100.0
Bactrocera occipitalis	< 1	0	0	0

Discussion

I undertook climate matching for 17 of the 19 non-native fruit fly species currently absent from Australia but that have been recognised a posing a substantial threat to this continent (National Plant Biosecurity Status Report 2017). For the 11 species for which there is a match between climate in Australia and the species known range, I quantified the relative establishment likelihood under current and future climate by considering a key arrival pathway (i.e. the movement of people entering Australia from host countries) and the likely distribution of host plants. As such, this work builds upon previous studies that have assessed the risk posed by fruit flies based primarily on the output of habitat suitability models (Yonow and Sutherst 1998, Sutherst et al. 2000, Kriticos 2007, Stephens et al. 2007, Ma et al. 2011, Ni et al. 2012, Fu et al. 2014, Qin et al. 2015, Kumar et al. 2016, Stephens et al. 2016, Zeng et al. 2019). It also complements the approach of Hill et al. (2016) who undertook a global assessment of the invasion potential of 12 tephritid pests (six of which were included in this chapter), based upon climate suitability, fruit production and trade indices.

Of the 11 species for which I estimated relative establishment likelihood, *Bactrocera dorsalis*, *Zeugodacus cucurbitae* and, to a lesser extent, *B. latifrons*, are likely to pose the greatest threat to horticulture in Australia. Tolerating climates from tropical to warm temperate, all three species are broad ranging throughout Africa, Asia and Oceania, and have been reported in other continents (CABI 2019). *B. dorsalis* has been found in 75 countries (Zeng et al. 2019). In contrast, most of the remaining eight species are primarily found in south-east Asia and Oceania.

In this study, I used the ExDet algorithm (Mesgaran et al. 2014) to detect areas with climatic conditions that match those in the tephritids' established ranges. A strength of this approach is that it identifies areas with univariate similarity (i.e. where each of a set of key climate variables fall within the range of values found in areas where the species is established), while also considering novel combinations of these variables (i.e. their correlations). This is a critical but frequently overlooked aspect of model development, providing an indication of the reliability of model transfer to conditions beyond the model training area.

Any correlative climate matching approach or species distribution model will be dependent upon the existence of a minimum number of occurrence records and the assumption that these records accurately capture the climate niche of the species. In the current study, I was unable to undertake climate matching for *B. facialis* and *B. psidii* due to insufficient occurrence records. Both of these species are currently only found in Pacific Islands. Similarly, the six species for which there was no climate match between Australia and their known ranges (i.e. *B. kandiensis*, *B. kirki*, *B. melanotus*, *B. passiflorae*, *B. trivialis*, *B. xanthodes*) are also currently confined to islands. Whether their current distribution is limited by geography rather than climate is unknown. However, these species could occur in broader climates than their native ranges. For example, a number of studies have highlighted that the climate of species' native ranges are not necessarily useful proxies of the climate breath of invasive populations (Beaumont et al. 2009, Bradley 2009, Gallagher et al. 2010). As such, caution must be applied to the results of my study, as the proportion of Australia that has suitable conditions for these species may be greater than what my analysis indicates.

A key pathway via which many exotic species enter a non-native country is the arrival of passengers from the countries in which these species are already present. Fruit flies, in particular, are frequently transported by air passengers (Putulan et al. 2004, Leibhold et al 2006). From the perspective of exotic fruit flies entering Australia, the greatest risk may lie in passengers from Indonesia and the USA, as six of the 11 species are present in both of these countries and more than 1,870,000 passengers arrive from these countries annually. Similarly, the risk posed by the ~ 2,000,000 passengers disembarking from flights from China, where *B.*

dorsalis, *B. latifrons* and *Z. cucurbitae* are present, is high even though Australia has a rigorous quarantine and biosecurity detection program (Leibhold et al. 2006). While I focus on the air passenger pathway, other pathways exist by which fruit flies might arrive at, and potentially intrude beyond, Australia's borders. For example, thousands of tonnes of horticultural products are imported via sea and air, and for some species (e.g., *B. dorsalis, B. zonata* and *Z. cucurbitae*) all life stages can be transported via this pathway (CABI, 2019). Mail (particularly fruit) can also carry fruit flies (CABI, 2019). While analysis of these pathways is outside the scope of the present analysis, it is worthy of future attention.

There are considerable limitations to the air passenger data used in this study. Data on exact passenger numbers is lacking, hence I assumed that the maximum number of available seats on different routes is reflective of the relative number of passengers flying those routes. Data were also lacking regarding the carriage of passengers on indirect international flights. In addition, the relative proportion of passengers from different countries was kept constant under future scenarios, although it is possible that this will shift. Similarly, I assumed that the proportion of passengers that are tourists, and the dispersal of passengers upon arrival, will remain constant.

Moreover, I note that the analysis does not consider the potential necessity for horticultural industries to shift geographically to adapt to climate change. Analysing shifts in climatic suitability for horticultural crops is further complicated by our capacity to modify the environment (e.g. through irrigation), and thus was beyond the scope of this study.

Ideally, to estimate current and future establishment likelihood information would be available on the current distribution of host crops and simulations of which geographic regions are likely to contain suitable conditions for these crops in the future. Unfortunately, such information is either unavailable (in the case of detailed information on host species' current distributions) or requires additional simulations beyond the scope of this study (for future distributions). The primary accessible data for host crops consisted of either major regions for commercial crops (e.g. from industry reports) or ALUM data. A limitation of the former is that only general place names of key regions are included in industry reports. While the ALUM data are recorded at a spatial resolution of 50 m, the attribute classes are relatively coarse, clumping perennial and seasonal horticulture into nine and four classes respectively, rather than listing individual crop species. Hence, a key limitation of this study is that I applied the same layer of the distribution of horticultural regions for all 11 species.

Here, I have assessed the relative likelihood of 11 of 19 non-native invasive tephritid species entering Australia. This study could be extended to combine its outputs with data describing the costs incurred upon incursion and establishment, thereby providing a more detailed risk assessment. Clearly, such information is highly valuable for the horticultural industry as well as pest managers, as it enables appropriate ongoing surveillance and management strategies to be planned and initiated.

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Appendix 4 Supplementary Information

S1 Table. Projected changes in the area of similar habitat for 19 fruit fly species, under six future climate scenarios, relative to the current period. (1) *Anastrepha ludens* (2) *Bactrocera carambolae* (3) *Bactrocera dorsalis* (4) *Bactrocera facialis* (5) *Bactrocera kandiensis* (6) *Bactrocera kirki* (7) *Bactrocera latifrons* (8) *Bactrocera melanotus* (9) *Bactrocera occipitalis* (10) *Bactrocera oleae* (11) *Bactrocera passiflorae* (12) *Bactrocera psidii* (13) *Bactrocera trivialis* (14) *Bactrocera xanthodes* (15) *Rhagoletis fausta* (16) *Rhagolets indifferens* (17) *Rhagoletis pomonella* (18) *Toxotrypana curvicauda* and (19) *Zeugodacus cucurbitae.* For each species, the first column indicates the species name and the second column indicates the GCM (Global Climate Model) for three time periods: 2030, 2050 and 2070. Other columns: Total area in 100 km² refers to the total area of similar habitat for 19 species under current and future scenarios; % Similarity refers to the percentage of similar habitat for all 19 species under current and future conditions (the total area of Australia is 7,673,080 km²). For two species *Bactrocera facialis* and *Bactrocera psidii*, NA value refers unable to undertake climate matching by Exdet tool.

(1) *Anastrepha ludens*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Anastrepha ludens	Current	13630	18
Anastrepha ludens	CanESM _30	7743	10
Anastrepha ludens	CanESM _50	7285	9
Anastrepha ludens	CanESM _70	7268	9
Anastrepha ludens	ACCESS_30	11540	15
Anastrepha ludens	ACCESS_50	8079	11
Anastrepha ludens	ACCESS_70	6670	9
Anastrepha ludens	GFDL_30	7385	10
Anastrepha ludens	GFDL_50	6673	9
Anastrepha ludens	GFDL_70	6498	8
Anastrepha ludens	MIROC_30	11076	14
Anastrepha ludens	MIROC_50	10486	14
Anastrepha ludens	MIROC_70	8838	12
Anastrepha ludens	HadGEM2_30	9712	13
Anastrepha ludens	HadGEM2_50	9582	12
Anastrepha ludens	HadGEM2_70	7334	10
Anastrepha ludens	NorEsm_30	12128	16
Anastrepha ludens	NorEsm_50	11184	15
Anastrepha ludens	NorEsm_70	11198	15

(2) *Bactrocera carambolae*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera carambolae	Current	797	1
Bactrocera carambolae	CanESM _30	648	1
Bactrocera carambolae	CanESM _50	667	0
Bactrocera carambolae	CanESM _70	761	0
Bactrocera carambolae	ACCESS_30	435	1
Bactrocera carambolae	ACCESS_50	352	1
Bactrocera carambolae	ACCESS_70	262	0
Bactrocera carambolae	GFDL_30	721	1
Bactrocera carambolae	GFDL_50	506	0
Bactrocera carambolae	GFDL_70	359	0

Bactrocera carambolae	MIROC_30	469	1
Bactrocera carambolae	MIROC_50	363	1
Bactrocera carambolae	MIROC_70	286	0
Bactrocera carambolae	HadGEM2_30	575	1
Bactrocera carambolae	HadGEM2_50	388	0
Bactrocera carambolae	HadGEM2_70	336	0
Bactrocera carambolae	NorEsm_30	405	1
Bactrocera carambolae	NorEsm_50	337	1
Bactrocera carambolae	NorEsm_70	290	1

(3) *Bactrocera dorsalis*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera dorsalis	Current	63410	83
Bactrocera dorsalis	CanESM _30	54861	71
Bactrocera dorsalis	CanESM _50	37941	49
Bactrocera dorsalis	CanESM _70	33616	44
Bactrocera dorsalis	ACCESS_30	65078	85
Bactrocera dorsalis	ACCESS_50	46693	61
Bactrocera dorsalis	ACCESS_70	35534	46
Bactrocera dorsalis	GFDL_30	43387	57
Bactrocera dorsalis	GFDL_50	33768	44
Bactrocera dorsalis	GFDL_70	26546	35
Bactrocera dorsalis	MIROC_30	65459	85
Bactrocera dorsalis	MIROC_50	58661	76
Bactrocera dorsalis	MIROC_70	58457	76
Bactrocera dorsalis	HadGEM2_30	52133	68
Bactrocera dorsalis	HadGEM2_50	39733	52
Bactrocera dorsalis	HadGEM2_70	34198	45
Bactrocera dorsalis	NorEsm_30	68515	89
Bactrocera dorsalis	NorEsm_50	69583	91
Bactrocera dorsalis	NorEsm_70	65451	85

(4) *Bactrocera facialis*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera facialis	Current	NA	NA
Bactrocera facialis	CanESM _30	NA	NA
Bactrocera facialis	CanESM _50	NA	NA
Bactrocera facialis	CanESM _70	NA	NA
Bactrocera facialis	ACCESS_30	NA	NA
Bactrocera facialis	ACCESS_50	NA	NA
Bactrocera facialis	ACCESS_70	NA	NA
Bactrocera facialis	GFDL_30	NA	NA
Bactrocera facialis	GFDL_50	NA	NA
Bactrocera facialis	GFDL_70	NA	NA
Bactrocera facialis	MIROC_30	NA	NA
Bactrocera facialis	MIROC_50	NA	NA
Bactrocera facialis	MIROC_70	NA	NA
Bactrocera facialis	HadGEM2_30	NA	NA
Bactrocera facialis	HadGEM2_50	NA	NA
Bactrocera facialis	HadGEM2_70	NA	NA
Bactrocera facialis	NorEsm_30	NA	NA

Bactrocera facialis	NorEsm_50	NA	NA
Bactrocera facialis	NorEsm_70	NA	NA

(5) *Bactrocera kandiensis*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera kandiensis	Current	0	0
Bactrocera kandiensis	CanESM _30	0	0
Bactrocera kandiensis	CanESM _50	0	0
Bactrocera kandiensis	CanESM _70	0	0
Bactrocera kandiensis	ACCESS_30	0	0
Bactrocera kandiensis	ACCESS_50	0	0
Bactrocera kandiensis	ACCESS_70	0	0
Bactrocera kandiensis	GFDL_30	0	0
Bactrocera kandiensis	GFDL_50	0	0
Bactrocera kandiensis	GFDL_70	0	0
Bactrocera kandiensis	MIROC_30	0	0
Bactrocera kandiensis	MIROC_50	0	0
Bactrocera kandiensis	MIROC_70	0	0
Bactrocera kandiensis	HadGEM2_30	0	0
Bactrocera kandiensis	HadGEM2_50	0	0
Bactrocera kandiensis	HadGEM2_70	0	0
Bactrocera kandiensis	NorEsm_30	0	0
Bactrocera kandiensis	NorEsm_50	0	0
Bactrocera kandiensis	NorEsm_70	0	0

(6) *Bactrocera kirki*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera kirki	Current	0	0
Bactrocera kirki	CanESM _30	0	0
Bactrocera kirki	CanESM _50	0	0
Bactrocera kirki	CanESM _70	0	0
Bactrocera kirki	ACCESS_30	0	0
Bactrocera kirki	ACCESS_50	0	0
Bactrocera kirki	ACCESS_70	0	0
Bactrocera kirki	GFDL_30	0	0
Bactrocera kirki	GFDL_50	0	0
Bactrocera kirki	GFDL_70	0	0
Bactrocera kirki	MIROC_30	0	0
Bactrocera kirki	MIROC_50	0	0
Bactrocera kirki	MIROC_70	0	0
Bactrocera kirki	HadGEM2_30	0	0
Bactrocera kirki	HadGEM2_50	0	0
Bactrocera kirki	HadGEM2_70	0	0
Bactrocera kirki	NorEsm_30	0	0
Bactrocera kirki	NorEsm_50	0	0
Bactrocera kirki	NorEsm_70	0	0

(7) *Bactrocera latifrons*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera latifrons	Current	19006	25
Bactrocera latifrons	CanESM _30	10373	14

Bactrocera latifrons	CanESM _50	8154	11
Bactrocera latifrons	CanESM _70	8500	11
Bactrocera latifrons	ACCESS_30	17157	22
Bactrocera latifrons	ACCESS_50	11595	15
Bactrocera latifrons	ACCESS_70	9015	12
Bactrocera latifrons	GFDL_30	10307	13
Bactrocera latifrons	GFDL_50	7158	9
Bactrocera latifrons	GFDL_70	5928	8
Bactrocera latifrons	MIROC_30	16523	22
Bactrocera latifrons	MIROC_50	15088	20
Bactrocera latifrons	MIROC_70	14410	19
Bactrocera latifrons	HadGEM2_30	11892	15
Bactrocera latifrons	HadGEM2_50	9918	13
Bactrocera latifrons	HadGEM2_70	9917	13
Bactrocera latifrons	NorEsm_30	21626	28
Bactrocera latifrons	NorEsm_50	21005	27
Bactrocera latifrons	NorEsm_70	22291	29

(8) *Bactrocera melanotus*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera melanotus	Current	0	0
Bactrocera melanotus	CanESM _30	0	0
Bactrocera melanotus	CanESM _50	0	0
Bactrocera melanotus	CanESM _70	0	0
Bactrocera melanotus	ACCESS_30	0	0
Bactrocera melanotus	ACCESS_50	0	0
Bactrocera melanotus	ACCESS_70	0	0
Bactrocera melanotus	GFDL_30	0	0
Bactrocera melanotus	GFDL_50	0	0
Bactrocera melanotus	GFDL_70	0	0
Bactrocera melanotus	MIROC_30	0	0
Bactrocera melanotus	MIROC_50	0	0
Bactrocera melanotus	MIROC_70	0	0
Bactrocera melanotus	HadGEM2_30	0	0
Bactrocera melanotus	HadGEM2_50	0	0
Bactrocera melanotus	HadGEM2_70	0	0
Bactrocera melanotus	NorEsm_30	0	0
Bactrocera melanotus	NorEsm_50	0	0
Bactrocera melanotus	NorEsm_70	0	0

(9) *Bactrocera occipitalis*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera occipitalis	Current	18	0
Bactrocera occipitalis	CanESM _30	18	0
Bactrocera occipitalis	CanESM _50	6	0
Bactrocera occipitalis	CanESM _70	0	0
Bactrocera occipitalis	ACCESS_30	29	0
Bactrocera occipitalis	ACCESS_50	19	0
Bactrocera occipitalis	ACCESS_70	3	0
Bactrocera occipitalis	GFDL_30	9	0
Bactrocera occipitalis	GFDL_50	10	0
Bactrocera occipitalis	GFDL_70	1	0
Bactrocera occipitalis	MIROC_30	40	0
Bactrocera occipitalis	MIROC_50	39	0

Bactrocera occipitalis	MIROC_70	8	0
Bactrocera occipitalis	HadGEM2_30	6	0
Bactrocera occipitalis	HadGEM2_50	1	0
Bactrocera occipitalis	HadGEM2_70	0	0
Bactrocera occipitalis	NorEsm_30	33	0
Bactrocera occipitalis	NorEsm_50	65	0
Bactrocera occipitalis	NorEsm_70	33	0

(10) *Bactrocera oleae*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera oleae	Current	70608	92
Bactrocera oleae	CanESM _30	61839	81
Bactrocera oleae	CanESM _50	44845	58
Bactrocera oleae	CanESM _70	34957	46
Bactrocera oleae	ACCESS_30	65270	85
Bactrocera oleae	ACCESS_50	54342	71
Bactrocera oleae	ACCESS_70	43549	57
Bactrocera oleae	GFDL_30	58206	76
Bactrocera oleae	GFDL_50	46301	60
Bactrocera oleae	GFDL_70	40312	53
Bactrocera oleae	MIROC_30	67237	88
Bactrocera oleae	MIROC_50	64115	84
Bactrocera oleae	MIROC_70	59552	78
Bactrocera oleae	HadGEM2_30	64588	84
Bactrocera oleae	HadGEM2_50	51942	68
Bactrocera oleae	HadGEM2_70	40388	53
Bactrocera oleae	NorEsm_30	66165	86
Bactrocera oleae	NorEsm_50	64198	84
Bactrocera oleae	NorEsm_70	60957	79

(11) *Bactrocera passiflorae*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera passiflorae	Current	0	0
Bactrocera passiflorae	CanESM _30	0	0
Bactrocera passiflorae	CanESM _50	0	0
Bactrocera passiflorae	CanESM _70	0	0
Bactrocera passiflorae	ACCESS_30	0	0
Bactrocera passiflorae	ACCESS_50	0	0
Bactrocera passiflorae	ACCESS_70	0	0
Bactrocera passiflorae	GFDL_30	0	0
Bactrocera passiflorae	GFDL_50	0	0
Bactrocera passiflorae	GFDL_70	0	0
Bactrocera passiflorae	MIROC_30	0	0
Bactrocera passiflorae	MIROC_50	0	0
Bactrocera passiflorae	MIROC_70	0	0
Bactrocera passiflorae	HadGEM2_30	0	0
Bactrocera passiflorae	HadGEM2_50	0	0
Bactrocera passiflorae	HadGEM2_70	0	0
Bactrocera passiflorae	NorEsm_30	0	0
Bactrocera passiflorae	NorEsm_50	0	0
Bactrocera passiflorae	NorEsm_70	0	0

(12) *Bactrocera psidii*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera psidii	Current	NA	NA
Bactrocera psidii	CanESM _30	NA	NA
Bactrocera psidii	CanESM _50	NA	NA
Bactrocera psidii	CanESM _70	NA	NA
Bactrocera psidii	ACCESS_30	NA	NA
Bactrocera psidii	ACCESS_50	NA	NA
Bactrocera psidii	ACCESS_70	NA	NA
Bactrocera psidii	GFDL_30	NA	NA
Bactrocera psidii	GFDL_50	NA	NA
Bactrocera psidii	GFDL_70	NA	NA
Bactrocera psidii	MIROC_30	NA	NA
Bactrocera psidii	MIROC_50	NA	NA
Bactrocera psidii	MIROC_70	NA	NA
Bactrocera psidii	HadGEM2_30	NA	NA
Bactrocera psidii	HadGEM2_50	NA	NA
Bactrocera psidii	HadGEM2_70	NA	NA
Bactrocera psidii	NorEsm_30	NA	NA
Bactrocera psidii	NorEsm_50	NA	NA
Bactrocera psidii	NorEsm_70	NA	NA

(13) *Bactrocera trivialis*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera trivialis	Current	0	0
Bactrocera trivialis	CanESM _30	0	0
Bactrocera trivialis	CanESM _50	0	0
Bactrocera trivialis	CanESM _70	0	0
Bactrocera trivialis	ACCESS_30	0	0
Bactrocera trivialis	ACCESS_50	0	0
Bactrocera trivialis	ACCESS_70	0	0
Bactrocera trivialis	GFDL_30	0	0
Bactrocera trivialis	GFDL_50	0	0
Bactrocera trivialis	GFDL_70	0	0
Bactrocera trivialis	MIROC_30	0	0
Bactrocera trivialis	MIROC_50	0	0
Bactrocera trivialis	MIROC_70	0	0
Bactrocera trivialis	HadGEM2_30	0	0
Bactrocera trivialis	HadGEM2_50	0	0
Bactrocera trivialis	HadGEM2_70	0	0
Bactrocera trivialis	NorEsm_30	0	0
Bactrocera trivialis	NorEsm_50	0	0
Bactrocera trivialis	NorEsm_70	0	0

(14) *Bactrocera xanthodes*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Bactrocera xanthodes	Current	0	0
Bactrocera xanthodes	CanESM _30	0	0
Bactrocera xanthodes	CanESM _50	0	0
Bactrocera xanthodes	CanESM _70	0	0
Bactrocera xanthodes	ACCESS_30	0	0

Bactrocera xanthodes	ACCESS_50	0	0
Bactrocera xanthodes	ACCESS_70	0	0
Bactrocera xanthodes	GFDL_30	0	0
Bactrocera xanthodes	GFDL_50	0	0
Bactrocera xanthodes	GFDL_70	0	0
Bactrocera xanthodes	MIROC_30	0	0
Bactrocera xanthodes	MIROC_50	0	0
Bactrocera xanthodes	MIROC_70	0	0
Bactrocera xanthodes	HadGEM2_30	0	0
Bactrocera xanthodes	HadGEM2_50	0	0
Bactrocera xanthodes	HadGEM2_70	0	0
Bactrocera xanthodes	NorEsm_30	0	0
Bactrocera xanthodes	NorEsm_50	0	0
Bactrocera xanthodes	NorEsm_70	0	0

(15) *Rhagoletis fausta*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Rhagoletis fausta	Current	6234	8
Rhagoletis fausta	CanESM _30	2512	3
Rhagoletis fausta	CanESM _50	1341	2
Rhagoletis fausta	CanESM _70	654	1
Rhagoletis fausta	ACCESS_30	2333	3
Rhagoletis fausta	ACCESS_50	1566	2
Rhagoletis fausta	ACCESS_70	900	1
Rhagoletis fausta	GFDL_30	3131	4
Rhagoletis fausta	GFDL_50	2021	3
Rhagoletis fausta	GFDL_70	1274	2
Rhagoletis fausta	MIROC_30	2652	4
Rhagoletis fausta	MIROC_50	1700	2
Rhagoletis fausta	MIROC_70	1367	2
Rhagoletis fausta	HadGEM2_30	2569	3
Rhagoletis fausta	HadGEM2_50	1454	2
Rhagoletis fausta	HadGEM2_70	873	1
Rhagoletis fausta	NorEsm_30	3264	4
Rhagoletis fausta	NorEsm_50	2234	3
Rhagoletis fausta	NorEsm_70	1384	2

(16) *Rhagolets indifferens*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Rhagoletis indifferens	Current	1413	2
Rhagoletis indifferens	CanESM _30	85	0
Rhagoletis indifferens	CanESM _50	12	0
Rhagoletis indifferens	CanESM _70	0	0
Rhagoletis indifferens	ACCESS_30	92	0
Rhagoletis indifferens	ACCESS_50	38	0
Rhagoletis indifferens	ACCESS_70	6	0
Rhagoletis indifferens	GFDL_30	27	0
Rhagoletis indifferens	GFDL_50	88	0
Rhagoletis indifferens	GFDL_70	13	0
Rhagoletis indifferens	MIROC_30	279	0

Rhagoletis indifferens	MIROC_50	77	0
Rhagoletis indifferens	MIROC_70	41	0
Rhagoletis indifferens	HadGEM2_30	145	0
Rhagoletis indifferens	HadGEM2_50	28	0
Rhagoletis indifferens	HadGEM2_70	5	0
Rhagoletis indifferens	NorEsm_30	230	0
Rhagoletis indifferens	NorEsm_50	54	0
Rhagoletis indifferens	NorEsm_70	4	0

(17) *Rhagoletis pomonella*

Species	GCM_Time period	Total Area in 100 km²	Similarity %
Rhagoletis pomonella	Current	10194	13
Rhagoletis pomonella	CanESM _30	5333	7
Rhagoletis pomonella	CanESM _50	4257	6
Rhagoletis pomonella	CanESM _70	2629	3
Rhagoletis pomonella	ACCESS_30	6397	8
Rhagoletis pomonella	ACCESS_50	4569	6
Rhagoletis pomonella	ACCESS_70	2625	3
Rhagoletis pomonella	GFDL_30	5088	7
Rhagoletis pomonella	GFDL_50	4172	5
Rhagoletis pomonella	GFDL_70	3465	5
Rhagoletis pomonella	MIROC_30	6825	9
Rhagoletis pomonella	MIROC_50	5647	7
Rhagoletis pomonella	MIROC_70	4798	6
Rhagoletis pomonella	HadGEM2_30	5312	7
Rhagoletis pomonella	HadGEM2_50	4520	6
Rhagoletis pomonella	HadGEM2_70	3274	4
Rhagoletis pomonella	NorEsm_30	6760	9
Rhagoletis pomonella	NorEsm_50	5993	8
Rhagoletis pomonella	NorEsm_70	4806	6

(18) *Toxotrypana curvicauda*

Species	GCM_Time period	Total number of grid cells	Similarity %
Toxotrypana curvicauda	Current	973.82	1
Toxotrypana curvicauda	CanESM _30	885.6	1
Toxotrypana curvicauda	CanESM _50	935.83	1
Toxotrypana curvicauda	CanESM _70	767.45	1
Toxotrypana curvicauda	ACCESS_30	1071.83	1
Toxotrypana curvicauda	ACCESS_50	1230.68	2
Toxotrypana curvicauda	ACCESS_70	1202.13	2
Toxotrypana curvicauda	GFDL_30	751.51	1
Toxotrypana curvicauda	GFDL_50	727.65	1
Toxotrypana curvicauda	GFDL_70	667.53	1
Toxotrypana curvicauda	MIROC_30	1007.91	1
Toxotrypana curvicauda	MIROC_50	1206.41	2
Toxotrypana curvicauda	MIROC_70	1677.11	2
Toxotrypana curvicauda	HadGEM2_30	851.68	1
Toxotrypana curvicauda	HadGEM2_50	680.28	1
Toxotrypana curvicauda	HadGEM2_70	928.16	1

Toxotrypana curvicauda	NorEsm_30	1580.56	2
Toxotrypana curvicauda	NorEsm_50	2108.83	3
Toxotrypana curvicauda	NorEsm_70	4067.11	5

(19) *Zeugodacus cucurbitae*

Species	GCM_Time period	Total number of grid cells	Similarity %
Zeugodacus cucurbitae	Current	76035	99
Zeugodacus cucurbitae	CanESM _30	73956	96
Zeugodacus cucurbitae	CanESM _50	60517	79
Zeugodacus cucurbitae	CanESM _70	45606	59
Zeugodacus cucurbitae	ACCESS_30	75422	98
Zeugodacus cucurbitae	ACCESS_50	67177	88
Zeugodacus cucurbitae	ACCESS_70	56392	73
Zeugodacus cucurbitae	GFDL_30	72579	95
Zeugodacus cucurbitae	GFDL_50	64769	84
Zeugodacus cucurbitae	GFDL_70	55871	73
Zeugodacus cucurbitae	MIROC_30	76040	99
Zeugodacus cucurbitae	MIROC_50	74836	98
Zeugodacus cucurbitae	MIROC_70	69364	90
Zeugodacus cucurbitae	HadGEM2_30	74967	98
Zeugodacus cucurbitae	HadGEM2_50	65112	85
Zeugodacus cucurbitae	HadGEM2_70	50329	66
Zeugodacus cucurbitae	NorEsm_30	76215	99
Zeugodacus cucurbitae	NorEsm_50	75815	99
Zeugodacus cucurbitae	NorEsm_70	74224	97

S2 Table. Area (100 km²) and their percentage of Australia projected to be similar for 19 exotic fruit flies under six future climate scenarios. In the column 'Climate scenarios', 0 refers to the area projected to be no similar across all six scenarios; 1 refers to the area projected to be similar under any one of the six scenarios…6 refers to the area projected to be similar under all six scenarios. For two species *Bactrocera facialis* and *Bactrocera psidii*, NA value refers unable to undertake climate matching by Exdet tool.

		Similarity					
Species	Climate scenarios	2030 (100 km²)	2030 %	2050 (100 km²)	2050 %	2070 (100 km²)	2070 %
Anastrepha ludens	0	62961	82	63118	82	64084	84
	1	1858	2	2862	4	2731	4
	2	1098	1	1813	2	2117	3
	3	1685	2	1060	1	1031	1
	4	1579	2	949	1	809	1
	5	1141	1	1743	2	1239	2
	6	6409	8	5185	7	4720	6
Bactrocera carambolae	0	75926	99	76011	99	75935	99
	1	172	0	193	0	367	0
	2	56	0	100	0	71	0
	3	56	0	50	0	47	0
	4	111	0	67	0	89	0
	5	101	0	51	0	42	0
	6	308	0	257	0	180	0
Bactrocera dorsalis	0	3537	7	5362	7	9648	13
	1	3391	4	10626	14	8760	11
	2	6270	8	11533	15	17175	22
	3	8131	11	7351	10	5023	7
	4	8056	10	6224	8	6911	9
	5	7185	9	8069	11	7305	10
	6	40160	52	27565	36	21909	29
Bactrocera facialis	0	NA	NA	NA	NA	NA	NA
	1	NA	NA	NA	NA	NA	NA
	2	NA	NA	NA	NA	NA	NA
	3	NA	NA	NA	NA	NA	NA
	4	NA	NA	NA	NA	NA	NA
	5	NA	NA	NA	NA	NA	NA
	6	NA	NA	NA	NA	NA	NA
Bactrocera kandiensis	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Bactrocera kirki	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0

	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Bactrocera latifrons	0	54323	71	54603	71	53429	70
	1	4169	5	7413	10	9340	12
	2	2499	3	3873	5	3197	4
	3	2893	4	2719	4	1484	2
	4	2605	3	333	0	1630	2
	5	1841	2	1908	2	2548	3
	6	8401	11	5882	8	5102	7
Bactrocera melanotus	0	0		0	0	0	0
	1	0		0	0	0	0
	2	0		0	0	0	0
	3	0		0	0	0	0
	4	0		0	0	0	0
	5	0		0	0	0	0
	6	0		0	0	0	0
Bactrocera occipitalis	0	76669	100	76650	100	76697	100
	1	26	0	42	0	24	0
	2	16	0	26	0	8	0
	3	10	0	9	0	2	0
	4	5	0	3	0	0	0
	5	4	0	1	0	0	0
	6	1	0	0	0	0	0
Bactrocera oleae	0	7357	10	10525	14	13695	18
	1	1261	2	2406	3	4630	6
	2	1791	2	7264	9	13525	18
	3	2386	3	4635	6	2538	3
	4	2986	4	3503	5	3765	5
	5	6812	9	9897	13	6416	8
	6	54137	71	38500	50	32161	42
Bactrocera passiflorae	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Bactrocera psidii	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Bactrocera trivialis	0	0	0	0	0	0	0
	1	0	0	0	0	0	0

	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Bactrocera xanthodes	0	0	0	0	0	0	0
	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	6	0	0	0	0	0	0
Rhagoletis fausta	0	73002	95	74107	97	75003	98
	1	437	1	342	0	226	0
	2	286	0	407	1	271	0
	3	387	1	343	0	348	0
	4	515	1	373	0	201	0
	5	394	1	311	0	252	0
	6	1710	2	847	1	429	1
Rhagoletis indifferens	0	76250	99	76608	100	76679	100
	1	247	0	52	0	41	0
	2	72	0	28	0	4	0
	3	62	0	9	0	6	0
	4	29	0	18	0	0	0
	5	14	0	5	0	0	0
	6	56	0	11	0	0	0
Rhagoletis pomonella	0	68865	90	70299	92	71427	93
	1	1065	1	647	1	607	1
	2	503	1	757	1	1000	1
	3	909	1	555	1	551	1
	4	428	1	353	0	431	1
	5	561	1	803	1	674	1
	6	4399	6	3318	4	2040	3
Toxotrypana curvicauda	0	74873	98	74152	97	72358	94
	1	607	1	1240	2	2570	3
	2	308	0	304	0	607	1
	3	116	0	162	0	252	0
	4	130	0	213	0	266	0
	5	125	0	256	0	359	0
	6	572	1	404	1	318	0
Zeogodacus cucurbitae	0	365	0	703	1	2330	3
	1	222	0	1056	1	4904	6
	2	462	1	5662	7	10508	14
	3	503	1	2237	3	3324	4
	4	1109	1	4078	5	5810	8
	5	2333	3	5139	7	6475	8
	6	71737	93	57854	75	43379	57

S3 Table. Major commercial fruits and vegetables host species to the Australian Horticulture Industry (see reference below). Pest status is based on Hancock et al (2006), where "major" indicates that there have been many records of the fly infesting that host.

Fruit fly species	Scientific name	Common name	Key region	Latitude	Longitude	State	Pest status
Anastrepha ludens	*Citrus x limon*	lemon	Mareeba	-16.995	145.423	Queensland	major
Anastrepha ludens	*Citrus x limon*	lemon	Burnett	-24.767	152.4	Queensland	major
Anastrepha ludens	*Citrus x limon*	lemon	Bundaberg	-24.866	152.348	Queensland	major
Anastrepha ludens	*Citrus x limon*	lemon	Lismore	-28.814	153.277	New South Wales	major
Anastrepha ludens	*Citrus x limon*	lemon	Riverland	-34.25	140.467	South Australia	major
Anastrepha ludens	*Citrus x limon*	lemon	Darwin	-12.463	130.842	Northern Territory	major
Anastrepha ludens	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Anastrepha ludens	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Anastrepha ludens	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Anastrepha ludens	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Anastrepha ludens	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	major
Anastrepha ludens	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Anastrepha ludens	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Anastrepha ludens	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Anastrepha ludens	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Anastrepha ludens	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Anastrepha ludens	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	major
Anastrepha ludens	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	major
Anastrepha ludens	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	major
Anastrepha ludens	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	major
Anastrepha ludens	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	major
Anastrepha ludens	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	major
Anastrepha ludens	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	major
Anastrepha ludens	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	major
Anastrepha ludens	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	major
Anastrepha ludens	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	major

Anastrepha ludens	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	major
Anastrepha ludens	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Anastrepha ludens	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Anastrepha ludens	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Anastrepha ludens	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Anastrepha ludens	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Anastrepha ludens	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Anastrepha ludens	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	major
Anastrepha ludens	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	major
Anastrepha ludens	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	major
Anastrepha ludens	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	major
Anastrepha ludens	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Anastrepha ludens	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Anastrepha ludens	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Anastrepha ludens	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Anastrepha ludens	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Anastrepha ludens	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Anastrepha ludens	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Anastrepha ludens	*Anacardium occidentale*	cashew nut	Ord River	-18.407	128.158	Western Australia	major
Anastrepha ludens	*Anacardium occidentale*	cashew nut	Burdekin River	-35.724	136.903	Queensland	major
Anastrepha ludens	*Anacardium occidentale*	cashew nut	Atherton Tablelands	-17.371	145.403	Queensland	major
Anastrepha ludens	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Anastrepha ludens	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Anastrepha ludens	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Anastrepha ludens	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	major
Anastrepha ludens	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	major
Anastrepha ludens	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	major
Anastrepha ludens	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	major
Anastrepha ludens	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	major
Anastrepha ludens	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	major

Anastrepha ludens	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	major
Anastrepha ludens	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	major
Anastrepha ludens	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Anastrepha ludens	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Anastrepha ludens	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Anastrepha ludens	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Anastrepha ludens	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera carambolae	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera carambolae	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera carambolae	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera carambolae	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera carambolae	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera carambolae	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera carambolae	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera carambolae	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera carambolae	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera carambolae	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera carambolae	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera carambolae	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera carambolae	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera carambolae	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera carambolae	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	major
Bactrocera carambolae	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera carambolae	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera carambolae	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera carambolae	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera carambolae	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major

Bactrocera carambolae	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	major
Bactrocera carambolae	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	major
Bactrocera carambolae	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera carambolae	*Citrus x limon*	lemon	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Citrus x limon*	lemon	Burnett	-24.767	152.4	Queensland	major
Bactrocera carambolae	*Citrus x limon*	lemon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Citrus x limon*	lemon	Lismore	-28.814	153.277	New South Wales	major
Bactrocera carambolae	*Citrus x limon*	lemon	Riverland	-34.25	140.467	South Australia	major
Bactrocera carambolae	*Citrus x limon*	lemon	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera carambolae	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	major
Bactrocera carambolae	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera carambolae	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	major
Bactrocera carambolae	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera carambolae	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera carambolae	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera carambolae	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera carambolae	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera carambolae	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera carambolae	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera carambolae	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera carambolae	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	major
Bactrocera carambolae	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	major
Bactrocera carambolae	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	major
Bactrocera carambolae	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major

Bactrocera carambolae	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	major
Bactrocera carambolae	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera carambolae	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera carambolae	*Anacardium occidentale*	cashew nut	Ord River	-18.407	128.158	Western Australia	major
Bactrocera carambolae	*Anacardium occidentale*	cashew nut	Burdekin River	-35.724	136.903	Queensland	major
Bactrocera carambolae	*Anacardium occidentale*	cashew nut	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Beerwah	-26.857	152.957	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Mareeba	-16.995	145.423	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Rollingstone	-19.043	146.391	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Yeppon	-23.128	150.746	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Wide Bay	-26.107	152.544	Queensland	major
Bactrocera carambolae	*Ananas comosus*	pineapple	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera dorsalis	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera dorsalis	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera dorsalis	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera dorsalis	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera dorsalis	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	major
Bactrocera dorsalis	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	major
Bactrocera dorsalis	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	major
Bactrocera dorsalis	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	major
Bactrocera dorsalis	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	major
Bactrocera dorsalis	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	major
Bactrocera dorsalis	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	major
Bactrocera dorsalis	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera dorsalis	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	major
Bactrocera dorsalis	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	major
Bactrocera dorsalis	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	major

Bactrocera dorsalis	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	major
Bactrocera dorsalis	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	major
Bactrocera dorsalis	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	major
Bactrocera dorsalis	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	major
Bactrocera dorsalis	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	major
Bactrocera dorsalis	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	major
Bactrocera dorsalis	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera dorsalis	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera dorsalis	*Prunus armeniaca*	apricot	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Prunus armeniaca*	apricot	Swan Hill	-35.333	143.549	South Australia	major
Bactrocera dorsalis	*Prunus armeniaca*	apricot	Renmark	-34.17	140.75	South Australia	major
Bactrocera dorsalis	*Prunus armeniaca*	apricot	Perth	-31.954	115.857	Western Australia	major
Bactrocera dorsalis	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	major
Bactrocera dorsalis	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	major
Bactrocera dorsalis	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	major
Bactrocera dorsalis	*Prunus avium*	cherry	Young	-34.314	148.298	New South Wales	major
Bactrocera dorsalis	*Prunus avium*	cherry	Orange	-33.284	149.101	New South Wales	major
Bactrocera dorsalis	*Prunus avium*	cherry	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Prunus avium*	cherry	Donnybrook	-33.577	115.821	Western Australia	major
Bactrocera dorsalis	*Prunus avium*	cherry	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera dorsalis	*Prunus avium*	cherry	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera dorsalis	*Prunus avium*	cherry	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera dorsalis	*Prunus avium*	cherry	Huon Valley	-43.033	147.033	Tasmania	major
Bactrocera dorsalis	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera dorsalis	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera dorsalis	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Bactrocera dorsalis	*Litchi chinensis*	lychees	Atherton Tablelands	-17.371	145.403	Queensland	major

Bactrocera dorsalis	*Litchi chinensis*	lychees	Rockhampton	-23.376	150.51	Queensland	major
Bactrocera dorsalis	*Litchi chinensis*	lychees	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Litchi chinensis*	lychees	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Bowen	-20.014	148.248	Queensland	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Chinchilla	-26.755	150.628	Queensland	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Riverina	-35	146	New South Wales	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Cowra	-33.834	148.691	New South Wales	major
Bactrocera dorsalis	*Citrullus lanatus*	watermelon	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera dorsalis	*Daucus carota subsp. sativus*	carrots	Gingin	-31.346	115.904	Western Australia	major
Bactrocera dorsalis	*Daucus carota subsp. sativus*	carrots	Preston	-32.882	115.656	Western Australia	major
Bactrocera dorsalis	*Daucus carota subsp. sativus*	carrots	Riverland region	-34.25	140.467	South Australia	major
Bactrocera dorsalis	*Daucus carota subsp. sativus*	carrots	Gippsland	-38.267	146.741	Victoria	major
Bactrocera dorsalis	*Daucus carota subsp. sativus*	carrots	Forth	-41.189	146.248	Tasmania	major
Bactrocera dorsalis	*Brassica oleracea var. capitata*	cabbages	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera dorsalis	*Brassica oleracea var. capitata*	cabbages	Sydney region	-33.865	151.21	New South Wales	major
Bactrocera dorsalis	*Brassica oleracea var. botrytis*	cauliflower	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera dorsalis	*Brassica oleracea var. botrytis*	cauliflower	Werribee	-37.902	144.658	Victoria	major
Bactrocera dorsalis	*Prunus dulcis*	almond	Riverina	-35	146	New South Wales	major
Bactrocera dorsalis	*Prunus dulcis*	almond	Swan Hill	-35.333	143.549	South Australia	major
Bactrocera dorsalis	*Prunus dulcis*	almond	Sunraysia region	-34.204	142.135	Victoria	major
Bactrocera dorsalis	*Prunus dulcis*	almond	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera dorsalis	*Prunus dulcis*	almond	Riverland region	-34.25	140.467	South Australia	major
Bactrocera dorsalis	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera dorsalis	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera dorsalis	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera dorsalis	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera dorsalis	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major

Bactrocera dorsalis	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	major
Bactrocera dorsalis	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	major
Bactrocera dorsalis	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera dorsalis	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera dorsalis	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera dorsalis	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera dorsalis	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Bactrocera dorsalis	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera dorsalis	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera dorsalis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera dorsalis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera dorsalis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera dorsalis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera dorsalis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera dorsalis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera dorsalis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Sydney Basin	-33.865	151.21	New South Wales	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Murray valley	-36.141	144.761	Victoria	major
Bactrocera dorsalis	*Diospyros kaki*	persimmon	Riverland	-34.25	140.467	South Australia	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Tully	-17.933	145.933	Queensland	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Innisfail	-17.522	146.031	Queensland	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Lakeland	-15.817	145	Queensland	major

Bactrocera dorsalis	*Musa x paradisiaca*	banana	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Coffs Harbour	-30.302	153.119	New South Wales	major
Bactrocera dorsalis	*Musa x paradisiaca*	banana	Carnarvon region	-24.881	113.659	Western Australia	major
Bactrocera dorsalis	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera dorsalis	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera dorsalis	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera dorsalis	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera dorsalis	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera dorsalis	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera dorsalis	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Beerwah	-26.857	152.957	Queensland	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Mareeba	-16.995	145.423	Queensland	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Rollingstone	-19.043	146.391	Queensland	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Yeppon	-23.128	150.746	Queensland	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Wide Bay	-26.107	152.544	Queensland	major
Bactrocera dorsalis	*Ananas comosus*	pineapple	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera dorsalis	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	major
Bactrocera dorsalis	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera dorsalis	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera dorsalis	*Capsicum annuum*	capsicum	Mildura	-34.207	142.137	Victoria	major
Bactrocera dorsalis	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera facialis	*Capsicum annuum*	Bell pepper	Bowen	-20.014	148.248	Queensland	major
Bactrocera facialis	*Capsicum annuum*	Bell pepper	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Capsicum annuum*	Bell pepper	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera facialis	*Capsicum annuum*	Bell pepper	Mildura	-34.207	142.137	Victoria	major
Bactrocera facialis	*Citrus x limon*	lemon	Mareeba	-16.995	145.423	Queensland	major
Bactrocera facialis	*Citrus x limon*	lemon	Burnett	-24.767	152.4	Queensland	major
Bactrocera facialis	*Citrus x limon*	lemon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Citrus x limon*	lemon	Lismore	-28.814	153.277	New South Wales	major

Bactrocera facialis	*Citrus x limon*	lemon	Riverland	-34.25	140.467	South Australia	major
Bactrocera facialis	*Citrus x limon*	lemon	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	major
Bactrocera facialis	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera facialis	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera facialis	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera facialis	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera facialis	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	major
Bactrocera facialis	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera facialis	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	major
Bactrocera facialis	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera facialis	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera facialis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera facialis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera facialis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera facialis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera facialis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera facialis	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera facialis	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera facialis	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera facialis	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera facialis	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera facialis	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major

Bactrocera facialis	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera facialis	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera facialis	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera facialis	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera facialis	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Bactrocera facialis	*Anacardium occidentale*	cashew nut	Ord River	-18.407	128.158	Western Australia	major
Bactrocera facialis	*Anacardium occidentale*	cashew nut	Burdekin River	-35.724	136.903	Queensland	major
Bactrocera facialis	*Anacardium occidentale*	cashew nut	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera facialis	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera facialis	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera facialis	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera facialis	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera kandiensis	*Anacardium occidentale*	cashew nut	Ord River	-18.407	128.158	Western Australia	major
Bactrocera kandiensis	*Anacardium occidentale*	cashew nut	Burdekin River	-35.724	136.903	Queensland	major
Bactrocera kandiensis	*Anacardium occidentale*	cashew nut	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera kandiensis	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera kandiensis	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	major
Bactrocera kandiensis	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	major
Bactrocera kandiensis	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	major
Bactrocera kandiensis	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kandiensis	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera kandiensis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera kandiensis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera kandiensis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera kandiensis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera kandiensis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kandiensis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera kandiensis	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera kirki	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera kirki	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major

Bactrocera kirki	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera kirki	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera kirki	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	major
Bactrocera kirki	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	major
Bactrocera kirki	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	major
Bactrocera kirki	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera kirki	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	major
Bactrocera kirki	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	major
Bactrocera kirki	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	major
Bactrocera kirki	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	major
Bactrocera kirki	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	major
Bactrocera kirki	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera kirki	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera kirki	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera kirki	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera kirki	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Bactrocera kirki	*Prunus dulcis*	almond	Riverina	-35	146	New South Wales	major
Bactrocera kirki	*Prunus dulcis*	almond	Swan Hill	-35.333	143.549	South Australia	major
Bactrocera kirki	*Prunus dulcis*	almond	Sunraysia region	-34.204	142.135	Victoria	major
Bactrocera kirki	*Prunus dulcis*	almond	Adelaide Hills	-34.911	138.707	South Australia	major
Bactrocera kirki	*Prunus dulcis*	almond	Riverland region	-34.25	140.467	South Australia	major
Bactrocera kirki	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera kirki	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera kirki	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera kirki	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera kirki	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera kirki	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	major
Bactrocera kirki	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera kirki	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	major

Bactrocera kirki	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera kirki	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kirki	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera kirki	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera kirki	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera kirki	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kirki	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera kirki	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera kirki	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera kirki	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera kirki	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera kirki	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera kirki	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera kirki	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera kirki	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera kirki	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera kirki	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kirki	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera kirki	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera kirki	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera kirki	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera kirki	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera kirki	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera kirki	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera kirki	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera kirki	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	major
Bactrocera kirki	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera kirki	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera kirki	*Capsicum annuum*	capsicum	Mildura	-34.207	142.137	Victoria	major
Bactrocera kirki	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major

Bactrocera latifrons	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera latifrons	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera latifrons	*Capsicum annuum*	capsicum	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Capsicum annuum*	capsicum	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Capsicum annuum*	capsicum	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera latifrons	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	major
Bactrocera latifrons	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera latifrons	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera latifrons	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera latifrons	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera latifrons	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera latifrons	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera latifrons	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera latifrons	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera latifrons	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera latifrons	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera latifrons	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	major
Bactrocera latifrons	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera latifrons	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera latifrons	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Darwin region	-12.463	130.842	Northern Territory	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Cowra	-33.834	148.69	New South Wales	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Riverina	-35	146	New South Wales	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Riverland region	-34.25	140.467	South Australia	major

Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera latifrons	*Cucumis melo var. cantalupensis*	rockmelon	Perth region	-31.954	115.857	Western Australia	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Darwin region	-12.463	130.842	Northern Territory	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Cowra	-33.834	148.69	New South Wales	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Riverina	-35	146	New South Wales	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Riverland region	-34.25	140.467	South Australia	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera latifrons	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Perth region	-31.954	115.857	Western Australia	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Bowen	-20.014	148.248	Queensland	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Darwin region	-12.463	130.842	Northern Territory	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Cowra	-33.834	148.69	New South Wales	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Riverina	-35	146	New South Wales	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Chinchilla	-26.755	150.628	Queensland	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera latifrons	*Citrullus lanatus*	watermelon	Kununarra	-15.778	128.744	Western Australia	major
Bactrocera melanotus	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera melanotus	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera melanotus	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera melanotus	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera melanotus	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera melanotus	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera melanotus	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera melanotus	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera melanotus	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major

Bactrocera melanotus	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	major
Bactrocera melanotus	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera melanotus	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera melanotus	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera melanotus	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera melanotus	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera melanotus	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera melanotus	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera melanotus	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera melanotus	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera melanotus	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera melanotus	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera melanotus	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera melanotus	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera melanotus	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera melanotus	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera melanotus	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera melanotus	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera melanotus	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera melanotus	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera occipitalis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera occipitalis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera occipitalis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera occipitalis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera occipitalis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera oleae	*Olea europaea*	olive	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera oleae	*Olea europaea*	olive	Riverina	-35	146	New South Wales	major
Bactrocera oleae	*Olea europaea*	olive	Boort	-36.115	143.724	Victoria	major
Bactrocera passiflorae	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera passiflorae	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major

Bactrocera passiflorae	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera passiflorae	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera passiflorae	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera passiflorae	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera passiflorae	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera passiflorae	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera passiflorae	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera passiflorae	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera passiflorae	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera passiflorae	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera passiflorae	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	major
Bactrocera passiflorae	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera passiflorae	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera passiflorae	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	major
Bactrocera passiflorae	*Citrus x limon*	lemon	Burnett	-24.767	152.4	Queensland	major
Bactrocera passiflorae	*Citrus x limon*	lemon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera passiflorae	*Citrus x limon*	lemon	Lismore	-28.814	153.277	New South Wales	major
Bactrocera passiflorae	*Citrus x limon*	lemon	Riverland	-34.25	140.467	South Australia	major
Bactrocera passiflorae	*Citrus x limon*	lemon	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	major
Bactrocera passiflorae	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera passiflorae	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera passiflorae	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera passiflorae	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera passiflorae	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera passiflorae	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major

Bactrocera passiflorae	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera passiflorae	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera passiflorae	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera passiflorae	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera passiflorae	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera passiflorae	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Bactrocera passiflorae	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera passiflorae	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera passiflorae	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera passiflorae	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera passiflorae	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera passiflorae	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera passiflorae	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Bactrocera passiflorae	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera passiflorae	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera psidii	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera psidii	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera psidii	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera psidii	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera psidii	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera psidii	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera psidii	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera psidii	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera psidii	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera psidii	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera psidii	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera psidii	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera psidii	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera psidii	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera psidii	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	SA	major

Bactrocera psidii	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera psidii	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera psidii	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera psidii	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera psidii	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Sydney Basin	-33.865	151.21	New South Wales	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Murray valley	-36.141	144.761	Victoria	major
Bactrocera psidii	*Diospyros kaki*	persimmon	Riverland	-34.25	140.467	South Australia	major
Bactrocera psidii	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera psidii	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera psidii	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera psidii	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Bactrocera psidii	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera psidii	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	major
Bactrocera psidii	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	major
Bactrocera psidii	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	major
Bactrocera trivialis	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera trivialis	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera trivialis	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	major
Bactrocera trivialis	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	major
Bactrocera trivialis	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera trivialis	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera trivialis	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera trivialis	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major
Bactrocera trivialis	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera trivialis	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	major
Bactrocera trivialis	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	major

Bactrocera trivialis	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera trivialis	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	major
Bactrocera trivialis	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera trivialis	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Bactrocera trivialis	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera trivialis	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Bactrocera trivialis	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera trivialis	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera trivialis	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera trivialis	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera trivialis	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera trivialis	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera xanthodes	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera xanthodes	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera xanthodes	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera xanthodes	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Bactrocera xanthodes	*Passiflora edulis*	passionfruit	Cooktown	-15.467	145.283	Queensland	major
Bactrocera xanthodes	*Passiflora edulis*	passionfruit	Daintree	-16.25	145.317	Queensland	major
Bactrocera xanthodes	*Passiflora edulis*	passionfruit	Mareeba	-16.995	145.423	Queensland	major
Bactrocera xanthodes	*Passiflora edulis*	passionfruit	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera xanthodes	*Passiflora edulis*	passionfruit	Tweed Valley	-28.183	153.55	New South Wales	major
Bactrocera xanthodes	*Citrus reticulata*	mandarin	Mareeba	-16.995	145.423	Queensland	major
Bactrocera xanthodes	*Citrus reticulata*	mandarin	Emerald	-23.523	148.158	Queensland	major
Bactrocera xanthodes	*Citrus reticulata*	mandarin	Mundubbera	-25.593	151.302	Queensland	major
Bactrocera xanthodes	*Citrus reticulata*	mandarin	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera xanthodes	*Citrus reticulata*	mandarin	Riverland	-34.25	140.467	South Australia	major
Bactrocera xanthodes	*Citrus x paradisi*	grapefruit	Murray Valley	-36.141	144.761	Victoria	major
Bactrocera xanthodes	*Citrus x paradisi*	grapefruit	Riverina	-35	146	New South Wales	major
Bactrocera xanthodes	*Citrus x paradisi*	grapefruit	Central Burnett	-24.767	152.4	Queensland	major
Bactrocera xanthodes	*Citrus x paradisi*	grapefruit	Riverland region	-34.25	140.467	South Australia	major

Bactrocera xanthodes	*Citrus x paradisi*	grapefruit	Perth region	-31.954	115.857	Western Australia	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Mareeba	-16.995	145.423	Queensland	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Burnett	-24.767	152.4	Queensland	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Lismore	-28.814	153.277	New South Wales	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Riverland	-34.25	140.467	South Australia	major
Bactrocera xanthodes	*Citrus x limon*	lemon	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera xanthodes	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major
Bactrocera xanthodes	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera xanthodes	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Bactrocera xanthodes	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera xanthodes	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Bactrocera xanthodes	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Bactrocera xanthodes	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Bactrocera xanthodes	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera xanthodes	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Bactrocera xanthodes	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Bactrocera xanthodes	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Bactrocera xanthodes	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Bactrocera xanthodes	*Capsicum annuum*	Bell pepper	Bowen	-20.014	148.248	Queensland	major
Bactrocera xanthodes	*Capsicum annuum*	Bell pepper	Bundaberg	-24.866	152.348	Queensland	major
Bactrocera xanthodes	*Capsicum annuum*	Bell pepper	Carnarvon	-24.881	113.659	Western Australia	major
Bactrocera xanthodes	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	major
Bactrocera xanthodes	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	major
Bactrocera xanthodes	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	major
Bactrocera xanthodes	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	major
Bactrocera xanthodes	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major
Bactrocera xanthodes	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Bactrocera xanthodes	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Rhagoletis fausta	*Prunus avium*	cherry	Young	-34.314	148.298	New South Wales	major

Rhagoletis fausta	*Prunus avium*	cherry	Orange	-33.284	149.101	New South Wales	major
Rhagoletis fausta	*Prunus avium*	cherry	Goulburn Valley	-37.034	145.125	Victoria	major
Rhagoletis fausta	*Prunus avium*	cherry	Donnybrook	-33.577	115.821	Western Australia	major
Rhagoletis fausta	*Prunus avium*	cherry	Manjimup	-34.241	116.146	Western Australia	major
Rhagoletis fausta	*Prunus avium*	cherry	Adelaide Hills	-34.911	138.707	South Australia	major
Rhagoletis fausta	*Prunus avium*	cherry	Sunraysia	-34.204	142.135	Victoria	major
Rhagoletis fausta	*Prunus avium*	cherry	Huon Valley	-43.033	147.033	Tasmania	major
Rhagoletis indifferens	*Prunus avium*	cherry	Young	-34.314	148.298	New South Wales	major
Rhagoletis indifferens	*Prunus avium*	cherry	Orange	-33.284	149.101	New South Wales	major
Rhagoletis indifferens	*Prunus avium*	cherry	Goulburn Valley	-37.034	145.125	Victoria	major
Rhagoletis indifferens	*Prunus avium*	cherry	Donnybrook	-33.577	115.821	Western Australia	major
Rhagoletis indifferens	*Prunus avium*	cherry	Manjimup	-34.241	116.146	Western Australia	major
Rhagoletis indifferens	*Prunus avium*	cherry	Adelaide Hills	-34.911	138.707	South Australia	major
Rhagoletis indifferens	*Prunus avium*	cherry	Sunraysia	-34.204	142.135	Victoria	major
Rhagoletis indifferens	*Prunus avium*	cherry	Huon Valley	-43.033	147.033	Tasmania	major
Rhagoletis pomonella	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	major
Rhagoletis pomonella	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	major
Rhagoletis pomonella	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	major
Rhagoletis pomonella	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	major
Rhagoletis pomonella	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	major
Rhagoletis pomonella	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	major
Rhagoletis pomonella	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	major
Rhagoletis pomonella	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	major
Rhagoletis pomonella	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	major
Rhagoletis pomonella	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	major
Rhagoletis pomonella	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	major
Toxotrypana curvicauda	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Toxotrypana curvicauda	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Zeugodacus cucurbitae	*Annona reticulata*	custard apple	Atherton Tablelands	-17.371	145.403	Queensland	major

Zeugodacus cucurbitae	*Annona reticulata*	custard apple	Sunshine Coast	-26.656	153.092	Queensland	major
Zeugodacus cucurbitae	*Annona reticulata*	custard apple	Lismore	-28.814	153.277	New South Wales	major
Zeugodacus cucurbitae	*Cucumis sativus*	cucumber	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Cucumis sativus*	cucumber	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Cucumis sativus*	cucumber	Riverland region	-34.25	140.467	South Australia	major
Zeugodacus cucurbitae	*Cucurbita moschata*	pumpkin	Murrumbidgee region	-34.8	145.883	New South Wales	major
Zeugodacus cucurbitae	*Cucurbita moschata*	pumpkin	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Cucurbita moschata*	pumpkin	Darling Downs region	-27.5	151.265	Queensland	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Darwin	-12.463	130.842	Northern Territory	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Katherine	-14.465	132.264	Northern Territory	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Mareeba	-16.995	145.423	Queensland	major
Zeugodacus cucurbitae	*Mangifera indica*	mango	Kununurra	-15.778	128.744	Western Australia	major
Zeugodacus cucurbitae	*Citrus sinensis*	orange	Riverina	-35	146	New South Wales	major
Zeugodacus cucurbitae	*Citrus sinensis*	orange	Murray Valley	-36.141	144.761	Victoria	major
Zeugodacus cucurbitae	*Citrus sinensis*	orange	Riverland	-34.25	140.467	South Australia	major
Zeugodacus cucurbitae	*Anacardium occidentale*	cashew nut	Ord River	-18.407	128.158	Western Australia	major
Zeugodacus cucurbitae	*Anacardium occidentale*	cashew nut	Burdekin River	-35.724	136.903	Queensland	major
Zeugodacus cucurbitae	*Anacardium occidentale*	cashew nut	Atherton Tablelands	-17.371	145.403	Queensland	major
Zeugodacus cucurbitae	*Averrhoa carambola*	carambola	Darwin	-12.463	130.842	Northern Territory	major
Zeugodacus cucurbitae	*Capsicum annuum*	bell pepper	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Capsicum annuum*	bell pepper	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Capsicum annuum*	bell pepper	Carnarvon	-24.881	113.659	Western Australia	major
Zeugodacus cucurbitae	*Capsicum annuum*	chilli	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Capsicum annuum*	chilli	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Capsicum annuum*	chilli	Carnarvon	-24.881	113.659	Western Australia	major
Zeugodacus cucurbitae	*Capsicum annuum*	chilli	Mildura	-34.207	142.137	Victoria	major
Zeugodacus cucurbitae	*Solanum lycopersicum*	tomato	Bowen	-20.014	148.248	Queensland	major

Zeugodacus cucurbitae	*Solanum lycopersicum*	tomato	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Solanum lycopersicum*	tomato	Lockyer Valley	-27.628	152.169	Queensland	major
Zeugodacus cucurbitae	*Solanum lycopersicum*	tomato	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Cucurbita pepo*	squash/zucchini	Atherton Tablelands	-17.371	145.403	Queensland	major
Zeugodacus cucurbitae	*Cucurbita pepo*	squash/zucchini	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Cucurbita pepo*	squash/zucchini	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Cucurbita pepo*	squash/zucchini	Bathurst	-33.417	149.581	New South Wales	major
Zeugodacus cucurbitae	*Cucurbita pepo*	squash/zucchini	Sunraysia region	-34.204	142.135	Victoria	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	beans	Innisfail	-17.522	146.031	Queensland	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	beans	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	beans	Gippsland	-38.267	146.741	Victoria	major
Zeugodacus cucurbitae	*Solanum melongena*	eggplant	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Solanum melongena*	eggplant	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Solanum melongena*	eggplant	Sydney region	-33.865	151.21	New South Wales	major
Zeugodacus cucurbitae	*Solanum melongena*	eggplant	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	green beans	Innisfail	-17.522	146.031	Queensland	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	green beans	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Phaseolus vulgaris*	green beans	Gippsland	-38.267	146.741	Victoria	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Darwin region	-12.463	130.842	Northern Territory	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Cowra	-33.834	148.69	New South Wales	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Riverina	-35	146	New South Wales	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Riverland region	-34.25	140.467	South Australia	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Sunraysia	-34.204	142.135	Victoria	major
Zeugodacus cucurbitae	*Cucumis melo var. cantalupensis*	rockmelon	Perth region	-31.954	115.857	Western Australia	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Darwin region	-12.463	130.842	Northern Territory	major

Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Cowra	-33.834	148.69	New South Wales	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Riverina	-35	146	New South Wales	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Riverland region	-34.25	140.467	South Australia	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Sunraysia	-34.204	142.135	Victoria	major
Zeugodacus cucurbitae	*Cucumis melo L. (Inodorus Group) 'Honey Dew'*	Honeydew melon	Perth region	-31.954	115.857	Western Australia	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Stanthorpe	-28.667	151.95	Queensland	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Batlow	-35.517	148.167	New South Wales	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Orange	-33.284	149.101	New South Wales	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Gippsland	-38.267	146.741	Victoria	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Yarra Valley	-37.657	145.447	Victoria	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Mornington Peninsula	-38.285	145.093	Victoria	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Huon Valley	-43.033	147.033	Tasmania	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Donnybrook	-33.577	115.821	Western Australia	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Manjimup	-34.241	116.146	Western Australia	major
Zeugodacus cucurbitae	*Malus domestica*	apple	Adelaide Hills	-34.911	138.707	South Australia	major
Zeugodacus cucurbitae	*Persea americana*	avocado	Atherton Tablelands	-17.371	145.403	Queensland	major
Zeugodacus cucurbitae	*Persea americana*	avocado	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Persea americana*	avocado	Sunraysia	-34.204	142.135	Victoria	major
Zeugodacus cucurbitae	*Persea americana*	avocado	Manjimup	-34.241	116.146	Western Australia	major
Zeugodacus cucurbitae	*Prunus persica*	peach	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Prunus persica*	peach	Sunraysia	-34.204	142.135	Victoria	major
Zeugodacus cucurbitae	*Prunus persica*	peach	Orange	-33.284	149.101	New South Wales	major
Zeugodacus cucurbitae	*Prunus persica*	peach	Young	-34.314	148.298	New South Wales	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Yarra Valley	-37.733	145.683	Victoria	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Gippsland	-37.584	147.767	Victoria	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Stanthorpe	-28.667	151.95	Queensland	major

Zeugodacus cucurbitae	*Pyrus communis*	pear	Batlow	-35.517	148.15	New South Wales	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Huon Valley	-43.033	147.033	Tasmania	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Adelaide Hills	-34.911	138.707	South Australia	major
Zeugodacus cucurbitae	*Pyrus communis*	pear	Manijmup	-34.241	116.146	Western Australia	major
Zeugodacus cucurbitae	*Prunus subg. Prunus*	plum	Goulburn Valley	-37.034	145.125	Victoria	major
Zeugodacus cucurbitae	*Prunus subg. Prunus*	plum	Young	-34.314	148.298	New South Wales	major
Zeugodacus cucurbitae	*Prunus subg. Prunus*	plum	Orange	-33.284	149.101	New South Wales	major
Zeugodacus cucurbitae	*Prunus subg. Prunus*	plum	Perth	-31.954	115.857	Western Australia	major
Zeugodacus cucurbitae	*Litchi chinensis*	lychees	Atherton Tablelands	-17.371	145.403	Queensland	major
Zeugodacus cucurbitae	*Litchi chinensis*	lychees	Rockhampton	-23.376	150.51	Queensland	major
Zeugodacus cucurbitae	*Litchi chinensis*	lychees	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Litchi chinensis*	lychees	Sunshine Coast	-26.656	153.092	Queensland	major
Zeugodacus cucurbitae	*Brassica oleracea var. botrytis*	cauliflower	Lockyer Valley	-27.628	152.169	Queensland	major
Zeugodacus cucurbitae	*Brassica oleracea var. botrytis*	cauliflower	Werribee	-37.902	144.658	Victoria	major
Zeugodacus cucurbitae	*Carica papaya*	pawpaw	Mareeba	-16.995	145.423	Queensland	major
Zeugodacus cucurbitae	*Carica papaya*	pawpaw	Tully	-17.933	145.933	Queensland	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Lockyer Valley	-27.628	152.169	Queensland	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Stanthorpe	-28.667	151.95	Queensland	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Windsor	-34.42	138.332	New South Wales	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Forbes	-33.385	148	New South Wales	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Robinvale	-34.586	142.774	Victoria	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Melbourne region	-37.813	144.963	Victoria	major
Zeugodacus cucurbitae	*Brassica oleracea var. italica*	brocolli	Adelaide Hills	-34.911	138.707	South Australia	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Yarra Valley	-37.733	145.683	Victoria	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Beerwah	-26.899	152.883	Queensland	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Camden	-34.054	150.695	New South Wales	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Adelaide Hills	-34.911	138.707	South Australia	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Wanneroo	-31.746	115.823	Western Australia	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Bullsbrook	-31.663	116.029	Western Australia	major
Zeugodacus cucurbitae	*Fragaria × ananassa*	strawberry	Albany	-35.027	117.884	Western Australia	major

Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Bundaberg	-24.866	152.348	Queensland	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Bowen	-20.014	148.248	Queensland	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Chinchilla	-26.755	150.628	Queensland	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Darwin	-12.463	130.842	Northern Territory	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Katherine	-14.465	132.264	Northern Territory	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Riverina	-35	146	New South Wales	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Cowra	-33.834	148.691	New South Wales	major
Zeugodacus cucurbitae	*Citrullus lanatus*	watermelon	Kununurra	-15.778	128.744	Western Australia	major

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S4 Table. The Australian Land Use and Mangement (ALUM) Classification system representing the potential distributions of host plant species for each of the 19 fruit fly species. Here Tertiary Landuse refers to specific commodities and their vegetation information regarding major commercial fruits and vegetables (ABARES 2016). Primary and Secondary Landuse relate to land use defined by the management objectives of the land manager (ABARES 2016). For other definitions see this link http://www.agriculture.gov.au/abares/aclump/land-use/alum-classification.

FRUIT FLY SPECIES	TERTIARY_LANDUSE	SECONDARY_LANDUSE	PRIMARY_LANDUSE
Anastrepha ludens	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	3.4.4 Vine fruits		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.4 Irrigated vine fruits		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera carambolae	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	3.4.4 Vine fruits		
	3.4.5 Shrub berries and fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.4 Irrigated vine fruits		
	4.4.5 Irrigated shrub berries and fruits		

	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera dorsalis	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	3.4.4 Vine fruits		
	3.4.5 Shrub berries and fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	3.5.0 Seasonal horticulture	3.5 Seasonal horticulture	3 Production from dryland agriculture and plantations
	3.5.1 Seasonal fruits		
	3.5.3 Seasonal vegetables and herbs		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.4 Irrigated vine fruits		
	4.4.5 Irrigated shrub berries and fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	4.5.0 Irrigated seasonal horticulture	4.5 Irrigated seasonal horticulture	4 Production from irrigated agriculture and plantations
	4.5.1 Irrigated seasonal fruits		
	4.5.3 Irrigated seasonal vegetables and herbs		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera facialis	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		

	3.4.4 Vine fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.4 Irrigated vine fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera kandiensis	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera kirki	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	3.4.4 Vine fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.4 Irrigated vine fruits		

	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera latifrons	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	3.5.0 Seasonal horticulture	3.5 Seasonal horticulture	
	3.5.1 Seasonal fruits		4 Production from dryland agriculture and plantations
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	
	4.4.1 Irrigated tree fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera melanotus	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera occipitalis	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations

	4.4.1 Irrigated tree fruits		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera oleae	3.4.2 Olives	3.4. Perennial horticulture	4 Production from dryland agriculture and plantations
	4.4.2 Irrigated olives	4.4 Irrigated perennial horticulture	
Bactrocera passiflorae	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.4 Vine fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.4 Irrigated vine fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera psidii	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.4 Vine fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.4 Irrigated vine fruits		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera trivialis	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.7 Perennial vegetables and herbs		

	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Bactrocera xanthodes	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Rhagoletis fausta	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
Rhagoletis indifferens	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
Rhagoletis pomonella	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations

	4.4.1 Irrigated tree fruits		
Toxotrypana curvicauda	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		
Zeugodacus cucurbitae	3.4.0 Perennial horticulture	3.4 Perennial horticulture	3 Production from dryland agriculture and plantations
	3.4.1 Tree fruits		
	3.4.3 Tree nuts		
	3.4.7 Perennial vegetables and herbs		
	3.4.8 Citrus		
	3.5.0 Seasonal horticulture	3.5 Seasonal horticulture	
	3.5.1 Seasonal fruits		
	3.5.3 Seasonal vegetables and herbs		
	4.4.0 Irrigated perennial horticulture	4.4 Irrigated perennial horticulture	4 Production from irrigated agriculture and plantations
	4.4.1 Irrigated tree fruits		
	4.4.3 Irrigated tree nuts		
	4.4.7 Irrigated perennial vegetables and herbs		
	4.4.8 Irrigated citrus		
	4.5.0 Irrigated seasonal horticulture	4.5 Irrigated seasonal horticulture	
	4.5.1 Irrigated seasonal fruits		
	4.5.3 Irrigated seasonal vegetables and herbs		
	5.4.0 Residential and farm infrastructure	5.4 Residential and farm infrastructure	5 Intensive uses
	5.4.2 Rural residential with agriculture		

S5 Table. Total area and percentage of Australia containing landuse associated with the host plant species for 19 exotic fruit fly species. Data are based on ALUM (see S4 Table).

Species	Landuse area 1 km² (total number of grid cells)	Landuse area 1 km² (%)
Anastrepha ludens	1311	1.71
Bcatrocera carambolae	1315	1.71
Bactrocera dorsalis	1357	1.77
Bactrocera facialis	1312	1.71
Bactrocera kandiensis	1302	1.70
Bactrocera kirki	1312	1.71
Bactrocera latifrons	1299	1.69
Bactrocera melanotus	1298	1.69
Bactrocera occipitalis	1206	1.57
Bactrocera oleae	25	0.03
Bactrocera passiflorae	1303	1.70
Bactrocera psidii	1302	1.70
Bactrocera trivialis	1297	1.69
Bactrocera xanthodes	1297	1.69
Rhagoletis fausta	193	0.25
Rhagoletis indifferens	193	0.25
Rhagoletis pomonella	193	0.25
Toxotrypana curvicauda	1294	1.69
Zeugodacus cucurbitae	1347	1.76

S6 Table. Total volume of passengers arriving from infested countries. Column Average pax pa refers the average (over 2016-2018) maximum number of air passenger seats on flights from known infested countries (source-BITRE).

Species	Country	Average pax pa
Anastrepha ludens	USA	1,894,115
Bactrocera carambolae	Brazil	364
	Brunei	92,753
	India	96,853
	India	96,853
	Indonesia	1,874,526
	Malaysia	1,718,524
	Singapore	3,649,587
	Thailand	1,079,566
	Vietnam	288,443
Bactrocera dorsalis	China	1,955,488
	India	96,853
	Indonesia	1,874,526
	Malaysia	1,718,524
	Papua New Guinea	273,252
	Philippines	416,970
	Singapore	3,649,587
	Sri Lanka	58,357
	Taiwan	288,608
	Thailand	1,079,566
	Vietnam	288,443
	Tonga	18,243
Bactrocera kandiensis	Sri Lanka	58,357
Bactrocera kirki	Fiji	545,581
	Tonga	18,243
	Western Samoa	35,248
Bactrocera latifrons	Brunei	92,753
	China	1,955,488
	Hong Kong SAR	1,642,432
	India	96,853
	Indonesia	1,874,526
	Japan	833,894
	Malaysia	1,718,524
	Sri Lanka	58,357
	Taiwan	288,608
	Thailand	1,079,566
Bactrocera melanotus	Cook Islands	14,178
Bactrocera occipitalis	Brunei	92,753
	Indonesia	1,874,526
	Malaysia	1,718,524
	Philippines	416,970
Bactrocera oleae	USA	1,894,115
Bactrocera passiflorae	Fiji	545,581
Bactrocera psidii	New Caledonia	116,008
Bactrocera trivialis	Indonesia	1,874,526
	Papua New Guinea	273,252
Bactrocera xanthodes	Cook Islands	14,178
	Fiji	545,581
	Nauru	21,802
	Tonga	18,243
Rhagoletis fausta	Canada	214,380
	Canada	214,380
	USA	1,894,115

Rhagoletis indifferens	Canada	214,380
	USA	1,894,115
Rhagoletis pomonella	Canada	214,380
	USA	1,894,115
Toxotrypana curvicauda	USA	1,894,115
Zeugodacus cucurbitae	Brunei	92,753
	China	1,955,488
	Hong Kong SAR	1,642,432
	India	96,853
	Indonesia	1,874,526
	Malaysia	1,718,524
	Papua New Guinea	273,252
	Philippines	416,970
	Sri Lanka	58,357
	Thailand	1,079,566

CHAPTER 5

Potential impacts of climate change on tephritid pest species

Abstract

Understanding the responses of pest species to climate change is imperative if monitoring programs and management strategies are to be effective in the future. Climate change will affect many insect species including those in the Tephritidae family, which include some of the world's most economically damaging horticultural pests. The goal of this review is to highlight how tephritid pests may respond to climate change. In doing so, I discuss the evidence for direct responses – range shifts, responses to extreme events, changes to species' phenology, and adaptive capacity – and indirect responses, such as via host plants or natural enemies. I found that few studies, beyond those using species distribution models to assess future range shifts, have been undertaken to explore the responses of tephritids to climate change. As such, the breadth of responses must be inferred from studies on related taxa. I highlight priority areas for future research, and the development of recent tools that could advance our understanding of the responses of tephritid species to climate change.

Keywords: adaptive capacity, climate change, elevated CO_2, natural enemies, phenological changes, tephritid pests.

Introduction

There is a clear fingerprint of anthropogenic climate change on a broad range of biological and ecological processes at multiple levels of biological organisation (Parmesan 2006, Scheffers et al. 2016). Species' ranges are shifting, phenological adjustments are occurring, and changes to meta-populations and community composition are taking place (Scheffers et al. 2016, Hoffmann et al. 2019). These changes have occurred in response to an increase in global mean annual temperature of ~1°C since 1910 (IPCC 2014). By the end of the 21st century, however, temperatures may be 2.6–4.8°C higher than present (IPCC 2014). As such, climate change will undoubtedly have consequences for the horticulture industry and the pests that threaten it.

Members of the insect family Tephritidae include some of the world's most economically damaging horticultural pests. This phytophagous family is amongst the largest in the insect order Diptera, with approximately 4,000 species across 500 genera (White and Elson-Harris 1992). Most of these species are found within temperate, tropical and subtropical regions of the world. Around 1,400 tephritid species probably develop in fleshy fruits (Norrbom et al. 1999), hence members of the family are commonly referred to as "true fruit flies". More than 350 species are of economic importance and occur in almost all fruit-growing regions of the world (White and Elson-Harris 1992, Plant Health Australia 2018) where they can cause serious damage to fruit, sometimes resulting in almost total crop failure (Qin et al. 2015).

Tephritids already cause significant economic damage to Australia's multi-billion-dollar horticulture industry (Plant Health Australia 2018). Other members of the family that are currently absent from Australia are likely to pose a substantial threat should they gain entry, and establish and spread. It is vital, therefore, that the mechanisms by which climate change could alter the threats these species pose, and consequences for species management, are understood. The goal of this review is to summarise knowledge of the potential responses of tephritids to climate change. I begin the review by introducing the four major economically significant genera of tephritid pests. I then discuss the key ways in which these species may directly respond to climate change, including via shifts in distribution, phenological changes and adaptation, as well as indirect responses, such as via the effects of elevated CO_2 on host plants, or the responses of natural enemies. Finally, I summarise the implications of climate change for the management of risks associated with tephritid pests.

Fruit fly species as pests

Within the Tephritidae, key pests of fruit production belong to four main genera: *Anastrepha* Schiner, *Bactrocera* Macquart, *Ceratitis* MacLeay and *Rhagoletis* Loew (White and Elson-Harris 1992, Malacrida et al. 2007), although some economically significant species also occur in other genera, such as *Dacus, Zeugodacus,* and *Toxotrypana*. *Anastrepha* is native to tropical and subtropical regions of the New World, *Bactrocera* is native to tropical Asia, the South Pacific and Australia regions, *Ceratitis* is an Afrotropical genus, and *Rhagoletis* is found in North and Central America, Europe and temperate Asia (Bateman 1972, Fletcher 1987, Headrick and Goeden 1998, Carey 2011). Below, I provide a brief overview of these four genera, then discuss the impacts of climate change on fruit fly pests in general.

Anastrepha

With more than 250 species endemic to the American tropics and subtropics, the genus *Anastrepha* is one of the largest in the Tephritidae family (Foote 1994, Norrbom 2004, Norrbom et al. 2012). At least seven species are major economic pests: *A. fraterculus* (Wiedemann); *A. obliqua* (Macquart); *A. ludens* (Loew); *A. grandis* (Macquart); *A. serpentina* (Wiedemann); *A. striata* (Schiner); and *A. suspensa* (Loew) (Hernández-Ortiz et al. 2004, Selivon et al. 2004, Selivon et al. 2005, Vera et al. 2006, Cáceres et al. 2009, Hernández-Ortiz et al. 2012). In Brazil, *Anastrepha* species have been reported to cause an annual loss of US $120–200 million to the horticulture industry (Zucchi et al 2004). Infestations of the highly polyphagous *A. fraterculus* in apple orchards in southern Brazil can cause economic losses estimated at US $110 million, while 40% of the total production of peaches may also be lost (Dias and Lucky 2017).

Anastrepha obliqua is also polyphagous, and ranges across Brazil (Uchôa and Nicácio 2010), Argentina (Guillén and Sánchez 2007), Bolivia (Ovruski et al 2009), Colombia (Canal 2010) and Venezuela (Katiyar et al 2000). It has been recorded on citrus, carambola, mango, guava, cashew, and pacific almonds (CABI Invasive Species Compendium 2012). The Mexican fruit fly, *A. ludens*, occurs in North America (Mexico and Florida) and Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras and Nicaragua), and frequently attacks fruits and vegetables sold at markets.

Bactrocera

Members of the genus *Bactrocera* present a substantial threat to horticultural crops due to their wide host ranges (Clarke et al. 2005). At least 440 species exist within this genus, which is distributed primarily across tropical Asia, the South Pacific, and Australia (White and Elson-Harris 1992). Relatively few species exist in Africa, with some having been introduced relatively recently (e.g., *B. dorsalis, B. latifrons and B. zonata*) (Lux et al. 2003, Drew et al. 2005, Mwatawala et al. 2009, De Meyer et al. 2012).

A number of *Bactrocera* species have been introduced to most fruit-producing regions of the world, often with major economic consequences. For instance, *B. carambolae* is native to the Indo-Australian region. It attacks at least 26 species worldwide, most of which have commercial interest (e.g., star fruit, mango, sapodilla, cherry, guava, jabuticaba, rose apple, jackfruit, breadfruit, orange, tangerine, tomato). This species was introduced to Southern America, probably via airplane flights from Indonesia (Oliveira et al. 2006). It is now found in the northern Brazilian states of Oiapoque and Amapá, where eradication programs have been established, as well as in neighboring French Guiana and Suriname (Oliveira et al. 2006). Its presence in Suriname led to drastic export reductions in the region, and threatened the export of fruits from Guyana to neighboring Caribbean countries (USDA/APHIS 2000).

The oriental fruit fly, *B. dorsalis* (Hendel) (Diptera: Tephritidae), originated in tropical and subtropical regions of Asia, and has become invasive worldwide (White and Elson-Harris 1992, Khamis et al. 2009, Clarke et al. 2019) due to its broad host range, large dispersal capacity and relatively wide climatic tolerance (Fletcher 1989, Duyck et al. 2004, Liu et al. 2011). Highly polyphagous, this species attacks more than 250 fruits and vegetables (Clarke et al. 2005, Drew et al. 2008). As such, *B. dorsalis* is regarded as a high-risk pest and has been listed as a quarantine species by many countries (Khamis et al. 2009).

Recently, three *Bactrocera s*pecies *(B. philippinensis* Drew and Hancock, *B. papayae* Drew and Hancock, and *B. invadens*) were declared junior synonyms of *B. dorsalis* (Drew & Romig 2013, Schutze et al. 2015). Combined, these synonymous species have greatly increased the geographic range of this pest, altering invasion patterns around the world (Vargaset al. 2015). This species threatens the commercial fruit industry in east and south-east Asia through higher costs of production and control, and new quarantine restrictions (Aketarawong et al 2014). It has caused losses of horticultural crops throughout Africa since it was first reported in 2003 (Lux et al. 2003). As a result of its presence, the USA banned importation of several fruits and vegetables from African countries (USDA-APHIS, 2008). Research from West Africa (Vayssières et al. 2005) and East Africa (Mwatawala et al. 2004, Ekesi et al. 2006, Rwomushana et al. 2008) has demonstrated that this species can become dominant in mango monocultures. In Benin, infestations of mango can lead to losses of more than 60% of fruits (Vayssières et al. 2007). As such, the direct damage caused by *B. dorsalis*, and other tephritid pests, seriously threatens the income, food security and livelihood of millions of families that produce and sell fresh fruit and vegetables across Africa (De Meyer et al. 2010).

Bactrocera zonata, the peach fruit fly, is ranked as one of the most economically significant species due to its high invasiveness and ability to cause serious economic damage to horticulture (Iwahashi & Routhier 2001, Ni et al. 2012). *Bactrocera zonata* originated in south and south-east Asia (Agarwal et al. 1999, Draz et al. 2016), but is now widely distributed from Asia to the Middle East and Africa. It causes an estimated €190 million of damage in Egypt per year (EPPO 2005), and poses a serious threat to the entire Mediterranean region (Duyck et al. 2004). This species attacks more than 50 fruits and vegetables (White and Elson-Harris 1992, Ni et al. 2012) as well as wild host plants from a range of families (Kapoor et al. 1983). It has also been suggested that under climate change *B. zonata* may expand is range poleward, including into Mediterranean regions (Ni et al 2012).

Ceratitis

The genus *Ceratitis* contains 89 species worldwide, including several species of agricultural importance (Virgilio et al. 2008). Chief among these is Medfly, *C. capitata* (Wiedemann), which is found in a broad range of climates across the world (Papadopoulos et al. 1996, Papadopoulos et al. 2001) and is considered one of the world's most destructive pests (Szyniszewska 2013). It originated in Africa (White and Elson-Harris 1992), invaded the Mediterranean region during the early 19th century, and from there spread to the rest of world (Headrick and Goeden 1996). It now occurs in most tropical and temperate regions, though some countries have successfully eradicated newly introduced (Penrose 1996) as well as established populations (Hendrichs et al. 1983, Fisher et al. 1985).

In warmer climates, Medfly can find various hosts throughout the year, and within several generations can build up very large populations in summer and autumn (Mavrikakis et al. 2000). It is highly polyphagous, feeding on around 300 host species (Papadopoulos et al. 2001, Papadopoulos et al. 2002). As such, eradication of Medfly outbreaks can be extremely costly. For instance, the cost of eradicating this species from Florida's Tampa Bay in 1997 cost US $25 million (Szyniszewska and Tatem 2014).

Rhagoletis

The genus *Rhagoletis* includes more than 65 species distributed throughout temperate, mesic environments (Yee et al. 2014). Several species are considered economically significant pests, including *R. pomonella, R. cingulata, R. indifferens, R. fausta, R. ribicola, R. zephyria*, and *R. mendax*. The apple maggot fly, *R. pomonella* (Walsh) (Diptera: Tephritidae), is a major pest of apples in western USA (Kumar et al. 2016). As such, both Canada and Mexico have required that apple imports from the USA undergo costly cold treatment to prevent the introduction of this pest (Krissoff et al. 1997). The eastern cherry fruit fly, *R. cingulata*, native to eastern North America (Bush 1966), is a key pest of cherries, rendering them unsuitable for consumption and processing, while the blueberry maggot fly, *R. mendax*, attacks blueberries in many parts of the eastern USA and Canada (Prokopy and Coli 1978, Neilson and Wood 1985). There is zero tolerance for these pest species in most of their host plant production areas: if not controlled these species seriously impact crop industries by reducing grower access to export markets as well as directly impacting the marketability of commercial crops (Zhao et al. 2007).

Direct effects of climate change on tephritid pests

Climate change will directly affect the behaviour, distribution, development, survival and abundance of many species, including insects (Bale et al. 2002, Altermatt 2010, Forrest 2016). To date there have been a number of studies modelling potential shifts to the distribution of suitable climate for tephritid species (e.g. Sutherst et al. 2000, Kriticos 2007, Stephen et al. 2007, Ni et al. 2012, Fu et al. 2014, Hill et al. 2016, Stephens et al. 2016, Sultana et al. 2017). Such responses may then alter the threat that tephritid pests pose to horticulture, meaning that programs currently in place to monitor and manage these species will need to preempt and adapt to such changes (Suckling et al. 2008).

Range shifts

Climate change may be a zero-sum game for invasive species (Hellmann et al. 2008), as it improves the suitability of a region for some species, while reducing it for others. As climate changes, many species including insects are predicted to shift their geographical ranges (Hughes 2000). However, it has been suggested that invasive species may respond to climate change differently to, and perhaps faster than, native species (Hellmann et al. 2008), potentially because invasive species have traits that allow them to capitalise on the various elements of climate change (Dukes and Mooney 1999). For instance, invasive species may be able to tolerate and track changing climates better than native species, as they tend to have greater dispersal capabilities (Hulme 2012) and/or broader climatic tolerances (Hellmann et al. 2008). In addition, as climate change is expected to shift native (or established exotic) species out of the conditions to which they are adapted, competitive resistance from established species may lessen in some places (Hellmann et al. 2008), possibly favouring establishment of new exotic species.

Many tephritid pests have tropical origins, with geographic ranges that are likely restricted by climate (see Merkel et al. 2019). These species may extend their ranges poleward in response to climate change, as indicated by projections from species distribution models (e.g. Stephens et al. 2007, Ni et al. 2012, Fu et al. 2014).

Using the semi-mechanistic model CLIMEX (Sutherst & Maywald 1985, Sutherst et al. 2007), both Hill et al. (2016) and Stephens et al. (2007) projected that under climate scenarios for 2070 and 2080, respectively, suitable conditions for *B. dorsalis* may expand northward in southern Europe, south-eastern regions of the USA, and southern China, but decline in Africa and South America. On the contrary, projections from a correlative model, Maxent, suggest that this species will pose an increasing risk to Africa and South America (Qin et al. 2019). However, direct comparisons of these studies must be viewed with caution, since they have very different calibration approaches, and use different datasets to describe climate conditions.

Models have also been used to assess potential geographic shifts in suitable conditions for other tephritid pests. Using CLIMEX, a comparison of climate suitability for the 2020s, compared to a 1961-1990 baseline, suggested that *Anastrepha obliqua* may expand its range polewards in areas too cold during the baseline, whereas suitability in tropical regions may decline (Fu et al. 2014). Additional analyses with CLIMEX by Hill et al. (2016) suggested that by 2070 contractions may continue to occur in some tropical regions (such as Brazil and sub-Saharan Africa), although expansions may occur in Mediterranean regions, south-eastern USA and temperate regions of Australia.

Europe is projected to become increasingly more suitable for *B. zonata* (Ni et al. 2012). In parts of Africa, *B. invadens* and *Dacus ciliatus* may also experience range increases, although suitable habitat for *Z. cucurbitae* and some *Ceratitis* species may decline (Masembe et al 2015). Similarly, in south-west India, warming by 2070 may result in moderate suitability of areas that are currently at little risk of *B. correcta* establishment (Choudhary et al 2019).

Hill et al. (2016) undertook a global analysis of the potential impact of climate change on 12 tephritid pests. For several species, tropical regions in South America and sub-Saharan Africa may become less suitable under scenarios for 2070 (e.g. *Anastrepha ludens*, *A. obliqua*, *Ceratitis capitata*, *C. rosa*, *B. dorsalis*, *B. latifrons*), although range margins for many species may extend poleward. However, for 11 of the 12 species, the primary direction of range shifts is projected to be eastward, likely due to complex interactions between temperature and precipitation. I also found that the potential Australian distributions of 11 tephritid pests of economic concern may shift southward (Chapter Three). In addition, both CLIMEX (Hill et al. 2016) and Maxent models from

Chapter Two and Three of this thesis predict that suitability of south-eastern Australia will increase for *B. tryoni* and *C. capitata*.

Phenological Changes

Over the past few decades, the phenology of a broad variety of taxa – including insects – has responded to global warming, particularly with respect to advancements in the timing of spring events (Parmesan & Yohe, 2003, Chambers et al. 2013, Beaumont et al. 2015, Hoffmann et al. 2019). As poikilotherms, the length and timing of phenological phases of insects, as well as the number of generations (voltinism) per year, is highly sensitive to external temperature changes (Hu et al. 2015, Rao et al. 2015). This has repercussions for over-wintering, diapause and aestivation.

Longer and warmer growing seasons may enable insect populations to complete additional generations each year (Forrest 2016), as has been recorded for some insects, including species of economic significance (Altermatt 2010, Bentz et al. 2010, Fand et al. 2014, Jönsson et al. 2009, Mitton and Ferrenberg 2012, Pöyry et al. 2011). For example, Altermatt (2010) reported that since 1980, 263 butterfly and moth species in Central Europe have shifted from being univoltine (a single generation per year) to bi- or even multi-voltine.

Comparisons of the voltinism of populations across a species' range can be used to inform its likely response to climate change. For example, populations of *B. tryoni* in tropical and subtropical regions may have 9–15 generations per year, whereas only 3–4 generations occur among populations in temperate regions (Meats 1981, Sutherst and Yonow 1998, Yonow et al. 2004). This suggests that as climate changes, the voltinism of species in temperate regions may increase. Since multi-voltinism has been linked to insect outbreaks, an increase in the abundance of pest species may occur in some regions. Model estimates for populations of *B. dorsalis, B. correcta* and *B. zonata* in India suggest a 15–24% reduction in generation time under future climate scenarios, resulting in ~5% higher infestation of mango fruits by 2050 (Choudhury et al. 2019). However, disruption of the developmental synchrony associated with multi-voltinism and host plant phenology may also reduce fitness (Choudhury et al. 2019). In some regions, high temperatures already limit the number of generations per year. For instance, within the Mediterranean Basin, *B. oleae* undergoes 4–6 generations per year with a break during the summer period when high temperatures and/or lack of fruit prevent breeding (Kapatos and Fletcher 1984). Further increases to temperature may result in longer summer periods with lower population numbers, although such temperature rises are also likely to negatively impact horticulture.

Higher temperatures during winter may decrease mortality rates of overwintering individuals, enabling populations to quickly regenerate in spring. For instance, all life-stages of *C. capitata* can survive mild winters (Papadopoulos et al. 1996, Rahman and Broughton 2019). Hence, both the previous year's adult population and newly emerged adults are likely to contribute to outbreaks in spring (Rahman and Broughton 2019).

Global warming may also alter the timing of diapause induction. Species of *Rhagoletis* are generally univoltine and undergo diapause (Rull 2009). Although metabolism is suppressed during diapause, warmer temperatures may result in higher oxygen consumption thereby increasing the rate at which nutrient reserves are consumed (see Dambroski and Feder 2007), which could negatively impact survivability.

Responses to extreme events

As climate changes, so too will the magnitude and frequency of extreme events such as heatwaves, cold spells, and extremes of precipitation. The tolerance of tephritids to high temperatures varies across species' life cycles. The highest temperatures tolerated by immature stages of *B. tryoni* typically do not exceed 38–40°C (Meats, 1984, Yonow et al 2004), while the survival rate of adults is negatively affected during winter (Fletcher, 1979, O' Loughlin et al 1984) when temperature falls below the torpor threshold of 2°C (Meats, 1976b, 1981). Short-term high temperature exposure can also decrease the reproductive capacity and survival rate of *C. capitata* (Zhang et al. 2019), although adults can survive 43°C (Nyamukondiwa & Terblanche 2009). Members of this species can also successfully overwinter in temperate climates (Mavrikakis et al. 2000, Papadopoulos et al. 2000): larvae have been found to survive at temperatures below 0°C in Central

Greece (Zervas et al. 1995, Papadopoulos et al. 1996), while all life stages can survive southern European winters (Fimiani 1989, Mavrikakis et al. 1997).

Zeugodacus cucurbitae adults can tolerate temperature as high as 51°C. Indeed, when exposed to 45°C individuals of this species produced 693 eggs per day compared with 666 eggs per day when exposed to 25°C (Zhou et al. 2019). Similarly, *B. dorsalis* was found to lay more eggs over two hours at temperatures of 40°C compared to at ambient temperatures of 25°C (Ren et al. 2010, as reported in Zhou et al. 2019). However, long term exposure to high temperatures inhibits the reproductive capacity and survival rate of this species (Jiang, 2006).

Extremes in rainfall can also influence survival and reproduction of fruit flies. For example, the abundance of *B. dorsalis* in China was found to decline when rainfall was below 50 mm monthly or above 250 mm monthly (Ye and Liu 2007). Similarly, immature stages of *B. tryoni* are highly vulnerable to both extreme dry or wet situations (Dominiak et al. 2000, Dominiak et al. 2003). During extreme dry conditions the fecundity of *B. tryoni* declined to ~32 eggs per week, whereas during sufficient rainfall ~190 eggs per week were produced (Bateman 1968). In temperate regions populations of *B. tryoni* may suffer from high mortality due to extreme dry conditions (Sonleitner 1973). Populations of *C. capitata* are generally inactive during heavy rainfall (Christenson and Foote 1960, Appiah et al. 2009), and adult mortality increases in extreme rainfall (Peñarrubia-María et al. 2012).

Hoffman et al. (2013) compiled a database of thermal tolerance estimates for multiple insect species, including their critical thermal maxima (CT_{max}). From this, Terblanche et al. (2015) quantified the warming tolerance (the difference between current habitat temperature and CT_{max}, compared to estimates of future temperatures) of 15 pest species including a number of tephritids. Under future projections, the warming tolerance of each species was reduced, particularly in the egg and larval life stages. This indicates that the vulnerability of earlier developmental stages to warming may limit the on-going persistence of these species (Terblanche et al. 2015).

Adaptation

Adaptation and tolerance to stressful environments are among the most important factors in defining invasion success. Populations that originate from variable environments are generally more tolerant of stressors and are more likely to become invasive compared with those from environments with more stable conditions (Lee & Gelembiuk 2008, Piiroinen et al. 2013). This is because high tolerance may enable organisms to persist under the new environmental conditions and allow sufficient time for adaptation to occur (Hoffmann & Sgrò 2011, Hoffmann 2017). Insect pest populations are typically characterised by their short generation times and large populations, resulting in high levels of genetic variability that facilitate higher rates of adaptation (Hoffmann 2017). These characteristics may allow pests to rapidly evolve tolerance to stresses associated with changing climatic conditions, for instance by adjusting their behaviour and physiology (Wong & Candolin 2015, Kelly 2019). Furthermore, should the speed at which populations are able to complete their life cycle and the number of generations per year increase, so too will the speed at which adaptation can occur (Terblanche et al. 2015). This, in turn, can increase the likelihood that a population can continue to exist *in situ* or expand into new geographic regions (Terblanche et al. 2015).

Evolutionary adaptation also plays a significant role in enabling insect species to tolerate climate change (Hoffmann & Sgrò 2011). Such changes are evidenced by rapidly changing allele frequencies in insects exploiting new conditions associated with a changing climate (Kanarek & Webb 2010, Merilä 2012, Kellermann & van Heerwaarden, 2019). Species' geographical ranges may also be modified due to evolutionary responses. For example, species have been shown to evolve a photoperiod response to climate change, enabling them to invade new areas and expand their geographic range (Urbanski et al. 2012, Sánchez-Guillén et al. 2016).

Insect crop pests may modify physiological responses with thermal stress through adaptive plasticity, i.e. plasticity of phenotypic traits that protect organisms in stressed environments and increase fitness under some circumstances (Buckley et al. 2017). Plasticity in response to variable climates generally involves diapause, but can also entail life-history changes such as reproductive suppression, and prolonged survival through winter (Sgrò et al. 2016, Regan et al. 2019, Tougeron et al. 2019). To date, there has been little research on adaptive responses of tephritids to climate change, yet this field of research is likely to be of substantial importance for proactively managing the threats these species pose in a warming world.

Indirect effects

Responses of host plants to climate change

Climate change is likely to alter the distributions, phenology and yield of wild host plants, as well as the suitability of regions for commercial crops. Hence, responses of tephritid pests to climate change will be partly driven by the responses of their host plants, as well as to changes in horticultural practices (e.g., selecting crops that are more resilient to climatic stress). For example, in Australia, warming and lower soil water content since the mid-20th century have resulted in earlier ripening of wine grapes (Webb et al. 2012). Consequently, harvesting in warmer temperatures (Webb et al. 2008), may potentially leading to increased exposure to fruit fly damage. In Mexico, as the availability of fruit declines, so too do population sizes of *A. ludens*, and the low abundance of adults during periods with cold temperatures is likely to be driven by scarcity of host fruits (Vanoye-Eligio et al. 2017). As such, if climate change increases the yield of their host plants, the abundance of these pests may also increase. Conversely, idiosyncratic responses of host plants and pests to climate change may result in phenological mismatches occurring, where the developing of pests no longer co-incide with the timing of fruit ripening of the host plants. However, to date, there have been few studies assessing mismatches.

Elevated CO_2 can indirectly affect insects via changes to the biochemistry of host plants (Jactel et al. 2019). Under higher concentrations of CO_2, the carbon-nitrogen ratio of leaves can increase, which can have negative consequences for the development of insect herbivores (Fajer et al. 1989, Jactel et al. 2019, Lincoln et al. 1993). However, this relationship between plant and insect responses remains unclear, and there is recent evidence that in response to higher CO_2, host plants alter their chemical defences via hormonal regulation to protect against insect herbivores (see Zavala et al. 2017). Meta-analyses also indicate that the relative consumption rates and development time of herbivorous insects increase due to CO_2-induced changes to host plants (Stiling and Cornelissen 2007, Robinson et al. 2012), while abundance significantly declines (Stiling and Cornelissen 2007). Similarly, changes to the nutritional quality and yield of fruits produced under higher CO_2 concentrations are likely to impact frugivorous insects (Clarke et al. 2011) such as tephritids, which spend their larval phase developing in fruit. To date, few studies on the consequences of climate change for insect–plant interactions have assessed this feeding guild of insects, although generally, changes to the quality of host plants are likely to have negative impacts on insect pests (Trebicki et al. 2017).

An additional consideration is the extent to which pests are likely to utilise alternate host plants should current hosts become unavailable due to phenological mismatches or changes in horticultural practices. Many fruit flies are highly polyphagous, increasing the likelihood of finding alternate hosts. Research continues to find new host species. For example, cucurbits were not recognised as hosts of *B. tyroni* (O'Loughlin, 1975), until recent laboratory experiments (Clarke et al. 2011). Grapes were previously listed as a poor host for B. tyroni (Jessup et al. 1998), however outbreaks in the Hunter Valley of New South Wales during 2007/2008 season saw high levels of damage to wine grapes (Loch, 2008).

Natural enemies

Natural enemies (parasitoids, predators and pathogens) are widely used to suppress fruit fly numbers, and are considered safe and relatively economical approaches to the control of these pests (Badii et al. 2015, Sarwar 2015). Natural enemies may feed on internally or externally on flies, ultimately leading to the death of the fly (Sarwar 2015). However, climate change may affect these natural enemies (Thomson et al. 2010, Helms et al. 2019), and changes to the phenology and geographic ranges of either the enemy or host can alter their chances of interactions (Thomson et al. 2010).

Thomson et al. (2010) outline five ways in which climate change can impact the enemies of insect pests: (1) changes to the pest's host plants, such as phenological shifts or changes to the nutritional quality of plants; (2) shifts in the distribution of the host plant or host insect; (3) changes in the response of the host insect or enemy to temperature or humidity; (4) a phenological mismatch between host insect and enemy; and (5) management of the crop and host insect. While there is little information on how climate change may alter interactions between tephritid pests and their natural enemies, studies of other taxa may be helpful for predicting general patterns to responses.

Differences in the thermal performance curves of parasitoids and their host insects have implications for the respective resilience of these species to climate change, and also for the potential for phenological cycles to decouple (Chidawanyika et al. 2019). The optimum temperatures for various parasitoids have frequently been found to be lower than those of their hosts (Furlong and Zalucki, 2017), indicating that parasitoids may be more vulnerable to climate warming than their hosts. In such cases, warmer temperatures may be detrimental to the success of parasitoids as biological controls in agro-ecosystems (Romo & Tylianakis, 2013).

A meta-analysis of studies assessing caterpillar–parasitoid interactions found lower levels of parasitism associated with increasing precipitation variability. Such changes in precipitation may be expected in the context of climate change, suggesting that the frequency and intensity of herbivore outbreaks may increase due to declines in their parasites (Stireman et al. 2005).

As climate variability increases, there may be a disconnection between parasitoids and their hosts if one of the interacting species develops faster in response to warming, or undergoes obligate diapause (Chidawanyika et al. 2019). For instance, if parasitoids emerge from the plant earlier than their herbivore host, a relatively large population of parasitoids might rapidly diminish the host population upon emergence of the latter, potentially leading to an absence of insects hosts and, ultimately, extirpation of the parasitoid population (Thomson et al. 2010). However, if the parasitoids emerge substantially earlier than their hosts, many may perish before the hosts appear, thereby advantaging the insect host (Thomson et al. 2010).

Opiine wasps (Hymenoptera: Braconidae), which are parasitoids, are frequently used in biocontrol programmes against tephritids (da Silva Gonçalves et al. 2017). Two species of tropical opiine parasitoids of fruit flies, *Diachasmimorpha kraussi* and *D. tyroni*, are endemic to Australia and have been used for biocontrol in other countries (Spinner et al. 2011). The presence of *D. kraussii* in fruit during heatwaves indicates that it is tolerant of high temperatures, unlike *D. tyroni* (Spinner et al. 2011), suggesting that it may continue to be a useful biocontrol agent as climate changes. However, although there are a number of studies developing protocols for culturing parasitoids or assessing their presence/absence amongst various fruits in the field, there appears to be little research into the comparative thermal requirements of fruit flies and their opiine parasitoids.

Pathogenic microorganisms (bacteria, viruses, fungi, protozoa and nematodes) are additional forms of biocontrol agents used to suppress tephritid populations (Badii et al. 2015). Entomopathogenic nematodes (e.g. Steinernematidae and Heterorhabditidae) have been used for control of the larvae and pupae of *A. ludens*, *B. tryoni* and *C. capitata* (Lezama-Gutiérrez et al. 2006, Malan and Manrakhan 2009, Langford et al. 2014), with mortality rates ranging between 14-96% (Dias et al. 2018). Laboratory studies of the effect of *Steinernema feltiae*, *S. carpocapsae* and *Heterorhabditis bacteriophora* on mortality of *B. tryoni* larvae at different temperatures found that all three nematodes caused significantly higher mortality at 25°C compared to 30°C (Langford et al. 2014). This may indicate limited effectiveness as biocontrol agents in warmer regions. However, the resilience of nematodes in natural environments to drier soils and higher temperatures, or to a lack of oxygen when soils are flooded, is unclear. This makes it difficult to determine how climate change and associated increases in extreme events may impact the effectiveness of these natural enemies for controlling fruit fly populations.

Climate change challenges the management of fruit flies

Climate change presents substantial challenges to the monitoring and management of tephritid pests. Climate matching or correlative species distribution models (SDM) are frequently used to predict the potential distribution of pest species, by comparing climatic conditions in regions of biosecurity concern with those in a pest's native range. These models, combined with knowledge of species' physiologies, suggest that within temperate regions species' ranges are likely to expand poleward as new areas become sufficiently warm to sustain populations. In the tropics, species already close to their critical thermal maxima may be vulnerable to heat stress, which could reduce population numbers and lead to extirpation. However, a key limitation of correlative SDMs is that they do not account for behavioural or physiological mechanisms that may enable organisms to tolerate climate change, such as by occupying micro-refugia (within backyard crops, agricultural regions or native vegetation), or via phenotypic plasticity or undergoing micro-evolution. In addition, the extent to which irrigation can buffer against climate change by altering microclimate is likely to be highly important (e.g. see Sutherst et al. 2000). Including this variable into SDMs is likely to be very difficult as there is little data on irrigation patterns. In addition, irrigation patterns will change on a short temporal cycle, making it difficult to include in SDMs which utilise long-term climate data. The impact of irrigation patterns are likely to be better explored using mechanistic models, or SDMs fitted with weather data.The economic costs of insect pests, such as tephritids, has led to comparatively more studies investigating their temperature and moisture requirements than for other species. Such information will be highly valuable for determining phenotypic plasticity and physiological limits. Ecological and physiological data can be useful proxies for understanding the potential for range shifts, and when information on responses to stresses or thermal tolerance limits, and overwintering abilities, are available this can be used to train more complex mechanistic distribution models (Terblanche et al. 2015), such as CLIMEX.

For most species, the capacity to adapt to climate change is unclear. However, several characteristics of pests and invasive species are considered to facilitate their adaptive capacity, such as rapid generation time, large population sizes, and an ability to tolerate a broad range of conditions. Recent advances have been made to couple SDMs with estimates of physiological limits, phenotypic plasticity, evolutionary adaptation and dispersal (Bush et al. 2016). This approach offers considerable potential to advance our understanding of the responses of pest species to climate change.

The geographic ranges and patterns of tephritid infestations will also impact the direct and indirect responses of their host plants to climate change. While elevated CO_2 is known to affect the biochemistry of host plants, such as by increasing the carbon-nitrogen ratio in leaves, it is less clear how this may impact the nutritional quantity and quality of fruits. A review of the crop ecophysiology literature to understand elevated CO_2-induced changes to vegetative and non-vegetative biomass, fruit yield and nutritional quality, and flow-on impacts to pest insects such as tephritids would be very valuable.

Management of fruit flies is challenging as various life-stages are protected from insecticides – eggs and larvae are in fruit, while third-instar larvae pupate in the soil – and countries are increasingly banning the use of broad-spectrum insecticides (see Dias et al. 2018, and references therein). Dias et al.'s (2018) global review of 533 publications on management tactics found that biocontrol was the most commonly studied tactic to suppress pest populations (29%), yet there may be declines in the efficacy of biocontrol agents due to lower thermal performance curves of some parasitoids. However, our ability to predict responses to climate change is constrained by the complexity of tri-trophic relationships (i.e. host plant-host insect-natural enemy) (see Thomson et al. 2010).

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CHAPTER SIX

Thesis Discussion and Conclusion

Tephritid fruit flies (Diptera: Tephritidae) are among the world's most economically damaging pests due partly to their wide climatic tolerance and broad host plant ranges, causing significant damage to horticultural industries globally (Bateman 1972, Fletcher 1987, Duyck et al. 2004, Qin et al. 2015, Hill et al. 2016, Stephen et al. 2016). In Australia, 46 tephritid species have been classified as "high priority pests" that present a significant risk to the nation's biosecurity (Plant Health Australia 2008). Eleven of these are currently found within Australia, of which nine are native (Hancock et al. 2000, Plant Health Australia 2018). Most of the high priority pest species infest multiple hosts and some of them are highly polyphagous (White and Elson-Harris 1992, Hancock et al. 2000, Clarke et al. 2005, Drew et al. 2008, Leblanc et al. 2012, Ni et al. 2012).

Around the world, horticultural industries have focused considerable effort researching and developing a broad array of techniques to manage these species, ranging from biological, chemical, and behaviour control to quarantine treatments (Dias et al. 2018). However, little consideration has been given as to how these pest species may respond to climate change, and the implications of this for pest control and management in the future. For example, in 2018, 246 "research, development and extension" projects were undertaken in Australia with a focus on pests and diseases of horticultural crops (National Plant Biosecurity Status Report 2018). Of these studies, only two (including Chapter Two of this thesis) included the term "climate change" in the title. It is also worth noting that the 2017 report (National Plant Biosecurity Status Report 2017) contained just a single mention of "climate change" in the main text. This was in the context that climate change will increase the "risk of an exotic forest pest incursion" (page 188). Reports from previous years did not mention climate change at all, with the exception of reporting that this PhD was being undertaken. It was not until the 2018 report that climate change was listed as a threat to plant health. This suggests that Australian horticultural industries are unlikely to be adequately informed about how climate change can alter risks posed by pests. My dissertation addresses this knowledge gap in the context of high priority fruit fly species. The key findings from my thesis are summarised below.

As climate changes, the distribution of suitable climatic conditions for some important tephritids in Australia will expand and move southward. This includes *Bactrocera tryoni* (Qfly), the most economically significant of Australia's tephritids (Chapter Two). The former Fruit Fly Exclusion Zone (FFEZ) in south-eastern Australia, as well as south-western regions of the country, are projected to face increased risk as climate changes (Chapter Two). The majority of other tephritid species that are currently present in the continent are likely to follow a similar pattern of range shifts (*B. bryoni*, *B. jarvisi*, *B. neuhumeralis*, *Ceratitis capitata*, *Zeugodacus cucurbitae*) (Chapter Three). As a result, commercially grown host plants in these regions face an increasing risk of infestation by these fruit fly species.

I also found that climate change may substantially increase the likelihood of establishment of several exotic tephritid pests that are currently absent from Australia (Chapter Four), such as *B. carambolae, B. dorsalis, B. latifrons, B. zonata, Anastrepha ludens* and *Toxotrypana curvicauda*. This is cause for considerable concern for Australian horticultural industries, and the increasing threat that these species pose should be factored into pre-border biosecurity activities, as well as into pest surveillance strategies. It is important to note that interactions with native species may moderate (or promote) establishment of exotic species. For example, *B. tryoni* is a relatively strong competitor, as evidenced by its competitive displacement of *C. capitata* when these species co-occur (Dominiak and Mapson 2017). This competitive advantage may preclude establishment success of exotic species regardless of climatic suitability (Duyck et al. 2004, Dominiak and Mapson 2017). Future research into the importance of such competitive exclusion in the context of exotic species establishment is warranted.

However, there are several major caveats that attention needs to be drawn to with respect to these three chapters. These include limitations of SDMs, responses of host plants to climate change, and changes to international and interstate movement of people who are one of the key ways in which plant pests spread.

Correlative species distribution models (SDMs) identify statistical relationships between species' occurrence data and environmental conditions, and are commonly used in risk assessments for invasive species (Hill and Thomson 2015). Because occurrence datasets reflect biotic constraints as well as non-climatic abiotic constraints (e.g. dispersal barriers, land use) on species' distributions, correlative SDMs describe the species' realized niche rather than its fundamental or potential niche (Jiménez-Valverde et al. 2011). This is problematic when biotic constraints vary between the native and invasive range (Beaumont et al. 2009), as it can lead to an underestimation of the tolerance of a species to climate.

Furthermore, SDMs and climate matching typically rely on a minimum number of occurrences, and therefore these techniques could not be applied to several species included in Chapter Four that are currently confined to small islands. These species are known to cause damage to crops that are cultivated in Australia, hence they pose a risk to Australian horticulture if an incursion takes place. Additional research involving laboratory-based experiments investigating critical thermal limits and desiccation rates of these species would be very useful for developing mechanistic models to identify which regions of Australia, if any, these species could survive in, and for informing about responses to climate change.

An important limitation of SDMs, in the context of climate change, is that these tools do not account for the plasticity or adaptive capacity of species, as they lack relevant information on fitness traits and their heritability (Huey et al. 2012). However, fruit flies are likely to have considerable adaptive capacity because of their short generation times and multi-voltinism. In Chapter Five, I briefly describe a recent development (*AdaptR*, Bush et al. 2016) which may help to advance the utility of SDMs for identifying regions at risk from pest invasions. This R package was developed to couple SDM outputs with information about species' physiological limits, phenotypic plasticity, ecology and adaptive capacity to predict range shifts that permit adaptation under climate change (Bush et al. 2016). However, until this approach has been undertaken for Australia's high priority pests, the limitations I have mentioned mean that we must be aware that areas projected by SDMs to have low or no suitability for a given pest species may actually be within the tolerance range of that species.

Presently, there is little information on how the distribution of horticultural industries may shift as a result of climate change. Clearly, the availability of host plants is of vital importance for the abundance and range of associated pest species. Throughout this thesis, I have assumed that regions in which horticulture is the dominant land use will remain as such in the future, although the type of crops grown may be changed.

Additional knowledge gaps associated with host plants that were highlighted in Chapter Five, include changes to biochemistry due to elevated CO_2, and how other characteristics such as yield and phenology, may shift with changes in temperature and precipitation patterns. Synthesis of the existing literature (particularly focusing on tephritids and their hosts) may help to bridge these knowledge gaps.

The risk that a pest species poses to a region will be influenced not only by climate and host plants, but also by the movement of goods and people. For example, although numerous strategies are used to control fruit flies in the former FFEZ, incursions still occurred. Dominiak et al. (2003) state that fruit flies are likely to have considerable difficulties moving between the towns of New South Wales and neighboring areas, due to the lack of host plants throughout the surrounding landscape matrix (Dominiak et al. 2003). However, it is unclear whether incursions are a result of individual flies flying in unaided, or whether they were introduced via infested fruit brought in by trade or the movement of people (Dominiak et al. 2000, Dominiak et al. 2003).

Within Chapter Four, I included information on the maximum number of air passengers coming into Australia, and their potential dispersal across the continent. However, the use of these data required several assumptions about the proportion of travellers that are tourists or returning residents, and how they disperse after arriving in Australia. In the absence of other data, I also assumed that proportions used in those analyses would remain stable into the future. Expanding this work to include the movement of fresh fruit products around the country and from international sources, with information on interception rates from goods and passengers, would aid with refining my approach.

Conclusion

This dissertation provides an analysis of high priority fruit fly species that pose substantial threats to Australian horticulture. While considerable research attention has been given to several of these species, the potential for climate change to alter their distributions and relative risks has been largely overlooked. My dissertation bridges this gap and provides explicit results based on data describing climate, soil, commercial plant hosts, and arrival and subsequent movement of air passengers from infested countries. My thesis illustrates the relationship between fruit fly pests and climate change, and the potential consequences for Australian horticulture, thereby providing value to the industry and to pest management. My findings also highlight the importance of vigilance to ensure the long-term security of these industries.

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